AN INVESTIGATION OF BLUETOOTH TECHNOLOGY FOR MEASURING TRAVEL TIMES ON ARTERIAL ROADS: A CASE STUDY ON SPRING STREET

A Thesis
Presented to
The Academic Faculty

by

Trung Vo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in the
School of Civil & Environmental Engineering

Georgia Institute of Technology
May 2011

AN INVESTIGATION OF BLUETOOTH TECHNOLOGY FOR MEASURING TRAVEL TIMES ON ARTERIAL ROADS: A CASE STUDY ON SPRING STREET

Approved by:

Dr. Michael P. Hunter, Advisor
School of Civil & Environmental Engineering
Georgia Institute of Technology

Dr. Randall L. Guensler
School of Civil & Environmental Engineering
Georgia Institute of Technology

Dr. Angshuman Guin
School of Civil & Environmental Engineering
Georgia Institute of Technology

Date Approved: April 4, 2011

To Sadie, my best friend and bride-to-be, for her support, grace, and love.

ACKNOWLEDGEMENTS

I would first like to thank Sadie, my fiancée, for her patience and encouragement during the writing of this thesis. I would also like to thank my parents, who are the hardest-working people that I know, and who have motivated me to strive for excellence. Without their generosity, provision, and love, I would not have succeeded at Georgia Tech. I would like to thank Will Morgan for encouraging me to pursue an undergraduate degree in civil engineering, which sparked my passion for transportation engineering.

I am extremely grateful for Dr. Michael Hunter's advisement, support, and encouragement during my time at Georgia Tech. I am also thankful for his thorough review of this thesis. I must also give credit to Dr. Angshuman Guin who laid the groundwork for the development of the field experiment and for his review of this thesis. I would also like to thank Dr. Randall Guensler for his review.

I owe many thanks to Stephanie Box, who served as my research partner and deserves much of the credit for the development and implementation of this field study. Credit is also due to Felipe Castrillon, Kate D'Ambrosio, Chris Rome, and Chris Toth, for volunteering to be probe vehicle drivers.

Finally, I must thank Jesus Christ, the motivator and catalyst of my life. Without Him, I would not be where I am and who I am today. He has compelled me to share His love and serve as a conduit for His grace. To Him be the glory, honor, and power.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iv
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF ABBREVIATIONS	xi
SUMMARY	xiii
CHAPTER 1: INTRODUCTION	14
1.1 Problem Statement	15
1.2 Study Objectives	16
1.3 Study Overview	16
CHAPTER 2: BACKGROUND AND LITERATURE REVIEW	17
2.1 General Travel Time Measurement Methods	17
2.1.1 Probe Vehicles	17
2.1.2 Global Positioning Systems and Geographic Information Systems	19
2.1.3 Automatic Vehicle Location	19
2.1.4 Automatic License Plate Recognition	20
2.1.5 Magnetic Signature Re-Identification	21
2.1.6 Radio-Frequency Identification Toll Tags	21
2.1.7 Summary	22
2.2 Bluetooth Technology and Specifications	23

2.2.1 Signals and Networking 23

2.2.2 Radio Interference 25

2.2.3 Radio Classes and Power 26

2.2.4 Data Transfer 26

2.2.5 Security and Media Access Control (MAC) Addresses 27

2.3 Bluetooth Travel Time Measurement Methods 28

2.3.1 Accuracy and Cost 28

2.3.2 Type and Placement of Bluetooth Readers 30

2.3.3 Outlying Data and Filters 30

2.3.4 Sample Size and Match Rates 32

2.3.5 Further Application 34

2.3.6 Summary 35

CHAPTER 3: METHODOLOGY 36

3.1 Objective 36

3.2 Field Measure of Travel Time Using Bluetooth 37

3.2.1 Independent Variables 37

3.2.1.1 Bluetooth Sites 38

3.2.1.2 Bluetooth Readers 39

3.2.1.3 Study Period 39

3.2.1.4 Probe Vehicles 40

3.2.1.5 Video Data Collection 40

3.2.2 Dependent Variables and Data Output 41

3.3 Summary 42

CHAPTER 4: EXPERIMENTAL DESIGN 43

4.1 Site Locations and Study Segment 43

4.2 Study Period 47

4.3 Bluetooth Reader Deployment 48

4.3.1 Bluetooth Adapters 48

4.3.2 Netbooks, Ubuntu, and PERL Scripts 48

4.3.3 Variable Heights 49

4.3.4 Offset from Roadway 49

4.4 Video Camera Data 49

4.4.1 Equipment 50

4.4.2 Traffic Volumes 51

4.5 Probe Vehicles 52

4.5.1 GPS Logger Devices 52

4.5.2 GPS Logger Travel Times 53

4.5.3 GPS Dilution of Precision 53

4.5.4 Bluetooth Emitter Devices 55

4.6 Summary 55

CHAPTER 5: RESULTS AND ANALYSIS 57

5.1 Site Performance Metrics 57

5.1.1 Detection Rates of Unique MAC Addresses 57

5.1.1.1 Traffic Volumes 58

5.1.1.2 Varying Heights 60

5.1.1.3 Two Readers at 10 Feet 63

5.1.1.4 Detection Rates 66

5.1.1.5 Probe Vehicle Devices 71

5.2 System Performance Metrics 72

5.2.1 Match Rates 73

5.2.2 Loss Rates 75

5.2.3 Travel Times and Travel Time Accuracy 76

5.2.3.1 GPS versus Probe Vehicle Bluetooth Devices 76

5.2.3.2 Non-Probe Vehicle Bluetooth Devices 83

5.2.3.3 Outlying Data Points 84

5.2.3.4 Travel Time Comparison 85

5.3 Summary 87

CHAPTER 6: CONCLUSION 89

6.1 Recommendations 89

6.2 Future Research 90

APPENDIX A 92

APPENDIX B 100

REFERENCES 109

LIST OF TABLES

Page

Table 1. Example Output from a Single Bluetooth Reader 41

Table 2. Ratings for DOP Values 54

Table 3. Estimated DOP Values for Site 1 and Site 2 During the Study Period 54

Table 4. Unique and Overlapping MACs Detected at Site 1 and Site 2 61

Table 5. Detection Rates for Each Bluetooth Reader Height 66

Table 6. Detection Rates for Site 1 and Site 2 67

Table 7. Percentage of Detected Passes for Class 1 Probe Devices by Bluetooth Reader 71

Table 8. Percentage of Detected Passes for Class 2 Probe Devices by Bluetooth Reader 71

Table 9. Unique MAC Addresses Detected between Site 1 and Site 2 73

Table 10. Descriptions of Probe Vehicle Bluetooth Devices 77

Table 11. GPS and Bluetooth Travel Times for Probe Vehicle 1 78

Table 12. Error in Bluetooth Travel Times for Probe Vehicle 1 78

Table 13. GPS and Bluetooth Travel Times for Probe Vehicle 2 81

Table 14. Error in Bluetooth Travel Times for Probe Vehicle 2 82

Table 15. Bluetooth Travel Time Outliers 85

Table 16. Bluetooth and GPS Travel Times 86

LIST OF FIGURES

Page

Figure 1. Example of Bluetooth Detection Zone 31

Figure 2. Map of Spring Street Study Segment 44

Figure 3. Map of Site 1 (Trump Towers Surface Parking Lot) 46

Figure 4. Map of Site 2 (Crum and Forster Building) 47

Figure 5. Permanent Vehicle Detection Camera View at Site 2 51

Figure 6. Five-Minute Traffic Volumes at Site 1 (Trump Towers Surface Parking Lot) 59

Figure 7. Five-Minute Traffic Volumes at Site 2 (Crum and Forster Building) 59

Figure 8. Overlap of Unique MAC Addresses Detected by Readers at Site 1 and Site 2 61

Figure 9. Unique MACs Detected by the Bluetooth Readers Placed at 10 Feet at Site 1 64

Figure 10. Unique MACs Detected by the Bluetooth Readers Placed at 10 Feet at Site 2 65

Figure 11. Traffic Volumes, Detections, and Unique MAC Addresses for Site 1 68

Figure 12. Traffic Volumes, Detections, and Unique MAC Addresses for Site 2 68

Figure 13. Five-Minute Detection Rates for Site 1 70

Figure 14. Five-Minute Detection Rates for Site 2 70

Figure 15. Unique MAC Addresses Detected at Sites 1 and 2 by Reader Height 74

Figure 16. Travel Time Comparison of GPS and Bluetooth Devices for Probe Vehicle 1 77

Figure 17. Travel Time Comparison of GPS and Bluetooth Devices for Probe Vehicle 2 80

Figure 18. Travel Times Produced from Matched MAC Addresses 83

Figure 19. Bluetooth and GPS Travel Times for Study Period 86

LIST OF ABBREVIATIONS

AFH	Adaptive Frequency Hopping
ALPR	Automatic License Plate Recognition
ANPR	Automatic Number Plate Recognition
ATIS	Advanced Travel Information System
ATMS	Advanced Traffic Management System
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
BDS	Bus Dispatch System
dBi	Decibel (Isotropic)
dBm	Decibel Milliwatt
DLM	Dynamic Linear Model
DMI	Distance-Measuring Instrument
DOP	Dilution of Precision
FHS	Frequency Hopping Synchronization
GHz	Gigahertz
GIS	Geographic Information System
GPS	Global Positioning System
HD	High-Definition
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific, and Medical
ITS	Intelligent Transportation System

kW	Kilowatt
MAC	Media Access Control
Mbit/s	Megabit per Second
MHz	Megahertz
mW	Milliwatt
OS	Operating System
OUI	Organizationally Unique Identifier
PAN	Personal Area Network
RFID	Radio-Frequency Identification
SLP	Sensor Location Problem
TT	Travel Time
Wi-Fi	Wireless Fidelity

SUMMARY

Research in the field of travel time measurement using Bluetooth technology has been an area of great interest in recent years as transportation professionals strive to increase the cost-effectiveness, accuracy, anonymity, and safety of travel time data collection methods. Commonly used travel time data collection methods include the use of inductive loops, video cameras, and probe vehicles. However, Bluetooth, a globally accepted wireless technology, serves as the medium being utilized by more and more transportation consultants, public agencies, and academics in the collection of travel time data.

This study seeks to develop a methodology for measuring travel times on arterial roads using Bluetooth technology. A literature review of general travel time methods and Bluetooth travel time methods was conducted to provide the context for a Bluetooth field deployment development and implementation. The study presents the deployment plan and data analysis of a case study conducted on Spring Street in Atlanta, Georgia. Variable heights, Bluetooth to Bluetooth interference, and detection of Bluetooth devices in probe vehicles are investigated and recommendations are suggested for future Bluetooth travel time studies.

CHAPTER 1: INTRODUCTION

The ability to effectively monitor traffic performance has proven to be a valuable asset to transportation agencies for several decades. Real-time traffic performance measurement is necessary to provide travelers and transportation agencies with accurate data that may be used to make decisions on their current trips, especially for roadways that experience high variability in traffic flow. Given methods for measuring the performance for single roadways to entire systems, transportation planners and engineers are able to base improvements on real operations, providing more effective and economical service on the systems for which they are responsible. One critically important performance metric is travel time, which is the time required to travel a defined length of roadway [1]. Travel times are most often provided to the public via changeable message signs (CMS) located on freeways [2], websites such as Georgia NaviGAtor (http://georgia-navigator.com/), or geographic information systems (GIS), such as Google Maps or MapQuest [3]. However, to be useful travel times must be accurate. Travel time accuracy is a measure of how closely a measured or estimated travel time matches the actual travel time. In addition, there is a great need for travel time reliability. Travel time reliability is a measure of the day-to-day consistency of travel times for a specific roadway [4]. It is only possible to know the travel time reliability of a corridor if accurate measures of day-to-day travel time are known. Accurate and reliable travel times will aid travelers in choosing the best route and transportation professionals in designing and planning for future improvements.

While many travel time measurement techniques exist, such as the utilization of inductive loops, video cameras, license plate matching, and floating car studies [1], limited success has been seen in their application to real-time travel time measurement. Radio-frequency identification (RFID) may be readily utilized in areas with tolls and on roadways which are traveled by drivers who already have RFID toll tags [5, 6]; however, implementation of such infrastructure may not be cost-effective or feasible. In recent years, Bluetooth has arisen as a new, accurate, and inexpensive tool to measure travel times on freeways and urban arterials [7]. Bluetooth technology also allows for anonymous travel time monitoring, matching the Media Access Control (MAC) addresses of Bluetooth devices (cell phones, GPS navigation devices, etc.) without obtaining or recording any personal information that may be associated with the user of the Bluetooth device. In addition, many devices that are Bluetooth-enabled provide the option to enable or disable "discovery mode" which allows the user to decide whether or not their device may be detected by other Bluetooth devices.

1.1 Problem Statement

Given the current development of Bluetooth technology to measure travel times, greater exploration is required to determine the optimal placement of Bluetooth readers. A Bluetooth reader's field placement may influence the ability of the reader to detect Bluetooth devices in passing vehicles. Placement variables include the height of the reader's antenna from the ground, the distance from the roadway, and the presence of other nearby readers. In addition, in the urban arterial environment the ability of an analysis technique to utilize the captured MAC addresses to measure vehicle travel time must also contend with potential sources of error such as the presence of pedestrians and bicyclists with Bluetooth devices, route diversions, vehicles dwelling in the detection zone for extended periods due to congestion resulting in multiple MAC address reads, and nearby stationary Bluetooth devices.

1.2 Study Objectives

This study will describe in detail a methodology by which Bluetooth technology may be utilized to measure travel times on urban arterial roads. Included in this methodology is an investigation of the impact of Bluetooth reader placement height on the number of MAC addresses detected. An evaluation of the accuracy of Bluetooth travel times via comparison to GPS-equipped probe vehicles is provided. Recommendations are also suggested for future field studies.

1.3 Study Overview

Chapter 2, the literature review, covers previously published literature relevant to travel time measurement on arterial roads. Travel time measurement using Bluetooth technology is given special emphasis. In addition, the background and technical specifications of Bluetooth technology are explained to aid the reader in understanding its use in traffic monitoring. Chapter 3 further outlines the experiment objectives and Chapter 4 describes the design of the experiment, presenting in detail the field experiment conducted on Spring Street in Atlanta, Georgia, on January 21, 2011. Chapter 5 describes the results of the Spring Street case study and the data analysis. Lastly, in Chapter 6 a summary of conclusions is offered along with recommendations for future research.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

A number of journal articles, presentations, and technical reports were consulted to establish a starting point and provide the context for the development of this study. Advanced traffic management systems (ATMS) and advanced traveler information systems (ATIS), two types of intelligent transportation systems (ITS), rely greatly on accurate traffic data [8]. This chapter describes known methods of providing travel time data. Firstly, general travel time methods were reviewed to provide a point of comparison for Bluetooth travel time methods. Secondly, Bluetooth technology is examined in detail. Lastly, an investigation was conducted on literature relevant to the application of Bluetooth technology in travel time measurement.

2.1 General Travel Time Measurement Methods

Methods that have been used by transportation professionals to measure travel times on freeways and arterial roads range from inductive loops, automatic license plate recognition (ALPR) systems, probe vehicle studies, and RFID tag reader systems. Numerous studies have been published on these travel time measurement tools as described below.

2.1.1 Probe Vehicles

Probe vehicles, vehicles operated by drivers who are instructed to traverse the roadway under study, are a commonly accepted method of collecting travel time data, along with other traffic performance metrics [9-17]. Probe vehicles may be outfitted with GPS devices which log time-stamped coordinates to measure travel times or a passenger may be tasked with manually recording travel times via a stopwatch.

FDOT's Manual on Uniform Traffic Studies [9] recommends the use of the floating car method for travel time and delay studies. In the floating car method, a probe vehicle passes as many cars along its route as those that pass the car. The manual recommends good weather and to not collect data during non-recurring traffic incident conditions. However, such a method is not readily able to be utilized for real-time travel time data collection and reporting.

Hunter et al. [12] developed a procedure to measure travel times on arterials using GPS-equipped probe vehicles. The proposed methods provided great flexibility in the interpretation of travel time results. The study addressed the potentially significant effort required to post-process the GPS data. It also addresses issues regarding the sample size of travel time data points, which are limited to the number of study segment traversals made by the probe vehicle.

An arrival time bias may exist in probe vehicle studies. To reduce this bias, Hellinga and Fu [11] propose a method in which the difference in average probe vehicle travel time and total population travel time are considered. The distribution of the travel times for all vehicles are used to weight each probe vehicle travel time. Video surveillance and loop detectors may be used to determine the travel times of the entire traffic flow.

Jun et al. [18] recommend that a modified Kalman filter be used to smooth GPS data to reduce random error. This study modified the conventional discrete Kalman filter algorithm to better control random errors in the GPS data and determined that this modified Kalman filter performed better than the least-squares spline approximation and kernel-based smoothing method.

2.1.2 Global Positioning Systems and Geographic Information Systems

Global positioning system (GPS) data may be integrated with geographic information systems (GIS) to compare geographic location with performance metrics (i.e. vehicle speeds, level of service, air quality, etc.) [17, 19, 20]. Taylor et al. [17] discussed the development of a method to integrate GPS data with GIS software. While displaying GPS data in GIS maps would help in transportation planning applications, the two data sets may not be completely accurate and thus, may not match consistently. Dailey and Cathey [19] also integrated GPS data with GIS maps and generated green, yellow, and red travel speed indicators on arterial roadways. Sarasua et al. [20] suggest a method to utilize GPS data and GIS to incorporate road gradient and vehicle location for use in transportation air quality modeling. However, a need for real-time traffic-monitoring and reporting still exists.

2.1.3 Automatic Vehicle Location

Transit buses and automatic vehicle location (AVL) may also be used to estimate travel times on arterials roads, as is the case in Portland, Oregon [21, 22], Chicago, Illinois [23], and King County, Washington [24]. TriMet, Portland's metropolitan transit agency, utilizes their bus dispatch system (BDS) to collect data while the buses are traveling their routes. Time-stamped location data are collected via AVL, and can thus provide travel time estimates. However, bus travel times may vary greatly from passenger car travel times on an arterial roadway as a result of the addition of passenger boarding and alighting time. The Chicago Transit Authority utilizes a similar methodology. The relationship between bus and non-transit travel time data are calculated using historical data and transit probe vehicle data to provide travel times which accurately portray actual conditions on an arterial [23].

Thornton [25] also investigated the use of transit buses as probe vehicles to measure travel times on arterial roads and proposed that radar-augmented transit buses can remove the bias associated with using bus travel times. An algorithm can be created to develop a simulation model which matches non-transit vehicle travel times.

2.1.4 Automatic License Plate Recognition

The capital and operating costs associated with computerized license plate matching are low, but this method cannot provide travel time or incident data in real-time [1]. Kennedy [26] suggests that the use of automatic license plate recognition (ALPR) systems is effective in monitoring traffic flow for both metropolitan and interstate highways. A typical ALPR system consists of an infrared camera and illuminator for each lane of traffic, one or more ALPR microprocessors, and a central server to hold the data. The data include vehicle license plate numbers, their associated timestamps and locations, and confidence levels of the license plate reads.

A source of error with ALPR is its ability to read license plate numbers in adverse lighting conditions. A two-day study was conducted along congested highways in Florida in November 2002 to test how ALPR performs in extreme sunlight [26]. Florida was chosen given the bright sunlight that is typically present to demonstrate ALPR’s effectiveness. High resolution and high contrast images were produced despite the extreme lighting conditions.

A travel time forecasting method has been tested on three motorway segments in southern England in 2008 [27]. Video data were processed by automatic number plate recognition (ANPR) software and combined with traffic flow data obtained via loop detectors to produce a dynamic linear model (DLM) to predict short-term traffic. In uncongested flow, forecasted travel times were typically within 10 percent of actual travel times. However, there was up to a 44.4 percent error when predicting travel times during periods of congestion. An accurate, real-time travel time reporting method that can operate regardless of lighting and traffic conditions is needed.

2.1.5 Magnetic Signature Re-Identification

Sun et al. [28] propose a multi-detector fusion method for calculating travel times on freeways. By matching the magnetic signatures of vehicles at two different points on a roadway, also known as vehicle re-identification, travel times may be estimated. This method's 90% re-identification rate warrants further investigation. Volling [29] also tested a magnetic signature re-identification system in San Diego. The test resulted in a 70% re-identification rate.

2.1.6 Radio-Frequency Identification Toll Tags

Radio-frequency identification (RFID) toll tag technology has been used to record travel times, taking advantage of existing toll tag infrastructure [6, 30, 31]. TMATCH, a Windows-based tag-matching software, was tested by Courage et al. [31]. This study states that the major advantage of using a toll-tag matching system is the larger sample size as compared to moving vehicle studies, though toll-tag matching also requires more complex planning and organization to implement.

Wright and Dahlgren [6] studied the FasTrak ETC system in the San Francisco Bay Area and found that toll tag systems typically cost less than loop detector and video detection methods. The capital costs for a single detector site for a six-lane highway is estimated at

$18,000 to $38,000, not including the cost of a required operations center. Additionally, annual operating costs range from $4,000 to $6,000 for every RFID reader site.

A major disadvantage of RFID reader systems is the dependence on market penetration of RFID toll tags [6]. An RFID system would not obtain a sufficient number of samples to accurately report travel times in areas where few vehicles are equipped with toll tags. In addition, RFID infrastructure is typically permanent and portable applications are limited. Finally, privacy concerns arise with the use of RFID tag matching, because personal information is tied to each toll tag. Although RFID systems may succeed in areas with preexisting RFID infrastructure, there is a need for a cost-effective, accurate, and anonymous travel time reporting method exists in areas with a small market penetration of toll tags.

2.1.7 Summary

There exist several methods of collecting travel time data, which include probe vehicle studies, license plate matching, and RFID toll tag technology. However, these methods each have inherent disadvantages ranging from high capital and operating costs, small sample size, privacy concerns, and inability to report travel times in real-time. A method for providing travel times accurately, cost-effectively, anonymously, and in real-time is needed. Bluetooth-based travel time data collection has the potential to be developed into such a method. Section 2.2 describes the Bluetooth technology.

2.2 Bluetooth Technology and Specifications

Invented in 1994 by engineers from Ericsson, a Swedish company, Bluetooth enables the sharing of music, images, and other data wirelessly over a personal area network (PAN) which is defined by the device's antenna [32]. The technical specifications and details of Bluetooth are described here, including frequencies and different types of antennas available along with their effective ranges. A radio frequency refers to rate at which radio signals are transmitted. The effective signal range of a Bluetooth device, which is defined by its antenna class, is the range at which other Bluetooth devices may be discovered and connected.

2.2.1 Signals and Networking

Bluetooth operates using low power and is intended to replace the cables which are commonly required to connect devices such as headsets and phones, keyboards and computers, and cameras and printers [32]. In contrast to more commonly used radio signals (TV, radio, etc.) which are broadcast over large areas, Bluetooth sends radio signals over short distances ranging from a minimum of 3 feet (1 meter) to more than 330 feet (100 meters) [32]. The radio waves are sent at frequencies from 2.402 GHz to 2.480 GHz as internationally agreed for the use of industrial, scientific, and medical (ISM) devices [33].

Before two Bluetooth devices can communicate, the devices must discover each other via two steps: inquiry and paging [34, 35]. The first step of this procedure may take 10.24 seconds. During this inquiring process, the Bluetooth devices hop on 32 channels, a subset of the 79 frequencies available for Bluetooth. These 32 channels consist of two 16-channel subsets called trains. The scan of each train lasts 0.01 seconds. In addition, Bluetooth specifies that each scan is repeated 256 times to provide adequate time to collect all inquiry responses from other Bluetooth devices. Also, Bluetooth specifies that at least three train switches must occur, resulting in two iterations of each train. Multiplying 2 trains by 2 iterations by 256 repetitions by 0.01 seconds equals a 10.24 seconds, which is the minimum time required for discovery of all Bluetooth devices within range [35].

After discovery, Bluetooth technology utilizes adaptive frequency hopping (AFH) and frequency hopping synchronization (FHS) to allow up to eight different devices to connect at the same time [33]. This is the paging step in Bluetooth communication. Adaptive frequency hopping forces a Bluetooth device to change between 79 unique and randomly chosen frequencies within the 2.4 GHz range at 1 MHz intervals at 1,600 hops a second. Frequency hopping reduces the likelihood of interference between any two devices, since it is very unlikely that two devices would be transmitting on the same frequency at the same moment. Even if a case arises where two devices happen to select the same frequency, the interference lasts only for a small fraction of a second as a result of the frequency hopping. Frequency hopping synchronization synchronizes the hopping sequence of two Bluetooth devices to allow the devices to continue to frequency hop while connected. Bluetooth devices that connect with one another automatically communicate over a personal area network (PAN), otherwise known as a piconet.

Although Bluetooth technology does not require line of sight, the signal attenuation of a Bluetooth device is influenced by physical obstacles [36]. Bluetooth signals are able to travel through glass and may propagate off of other reflective surfaces to establish a wireless connection. However, objects that obstruct the line of sight between two Bluetooth devices may decrease the likelihood that the devices will be able to connect. This characteristic of Bluetooth is important to this research and plays a role in the field deployment plan of the Spring Street case study.

2.2.2 Radio Interference

Because Bluetooth operates on the unlicensed 2.4 to 2.483 GHz ISM spectrum, it is negatively affected by other devices which use higher power, such as 802.11b (Wi-Fi), cordless phones, two-way radios, and microwave ovens [37]. Furthermore, Bluetooth piconets may interfere with other established Bluetooth piconets in the same area. This type of interference is called frequency dynamic interference, and the result is frequency dynamic noise [37]. All Bluetooth devices currently use adaptive frequency hopping to reduce signal interference. Signal degradation occurs as a result of two or more piconets occupying the same area [37]. This is a result of two Bluetooth devices attempting to transmit on the same frequency channel. A 5 percent efficiency loss occurs in the presence of 4 piconets, 11 percent with 10 piconets, and 21 percent with 20 piconets. Studies have shown that there is negligible signal degradation when wirelessly transmitting devices are more than two meters apart [36]. However, substantial signal degradation occurs within half a meter.

Lynch Jr. [38] studied co-channel interference in Bluetooth piconets in 2002. Although frequency hopping reduces interference from other devices operating on the same frequency, it introduces co-channel interference, which occurs when two Bluetooth devices hop to the same channel. When data packets are transmitted simultaneously on the same frequency in two overlapping piconets, a frequency collision occurs which results in the transmission failure. The data packets are then retransmitted on a different frequency. Several interfering piconets will decrease the data transfer rate of the Bluetooth devices connected to those piconets.

2.2.3 Radio Classes and Power

Although the Core Specification for Bluetooth requires a minimum range of 33 feet (10 meters), manufacturers are allowed to set their own limits to appropriately meet the needs of their products' intended users [32]. Class 3 radios are characterized by ranges of 3 feet (1 meter). Class 2 radios are more commonly found in mobile phone devices and must provide a range of at least 33 feet (10 meters). Finally, Class 1 radios must offer a minimum range of 330 feet (100 meters). Class 1 radios are typically used for industrial applications.

Bluetooth technology was designed to operate at very lower power [32]. Class 1 radios operate at a maximum of 100 mW or 20 dBm, while Class 2 radios, the most commonly used radios, function at 2.5 mW or 4 dBm. Class 3 radios operate at the rate of 1 mW or 0 dBm [32]. A typical laser pointer produces 5 mW of light power and a typical hearing aid consumes less than 1 mW. For further comparison, 1kW, which is 1000 mW, may be used to power a small electric heater.

2.2.4 Data Transfer

While Bluetooth consumes substantially less power than Wi-Fi devices, its data transfer is slower. The developers of Bluetooth have purposefully prioritized the use of low power over the rate of data transfer [32]. Bluetooth Version 1.2 has a maximum data transfer rate of 1 Mbit/s. Version 2.0 + EDR can transfer up to 3 Mbit/s, and Version 3.0 + HS can transfer data 24

Mbit/s [32]. These transfer rates may be compared to Wi-Fi (802.11b) which can transfer up to 54 Mbit/s.

2.2.5 Security and Media Access Control (MAC) Addresses

Like all wireless connections, Bluetooth sends signals that may be susceptible to interception by those who are wishing to access data without permission. Bluetooth's automatic connections are a benefit in terms of convenience, but may serve as a gateway through which unwanted data are received. Consequently, manufacturers will typically provide the option to enable and disable Bluetooth capabilities on their devices [36]. Commonly known as "discovery mode," this mode enables the device to be detected by other Bluetooth devices. Bluetooth devices with discovery mode enabled can be discovered by other devices via Bluetooth and thus, can establish connection with other devices.

Bluetooth technology uses the MAC-48 identifier format as defined by the Institute of Electrical and Electronics Engineers (IEEE) [39]. Consequently, every Bluetooth device is uniquely identified by a 48-bit MAC address, which consists of six pairs of hexadecimal digits. The first three groups of numbers are known as the organizationally unique identifier (OUI) which are specific to the device manufacturer, while the last three groups of numbers are unique to the device. In Bluetooth travel time measurement systems, the MAC address of every Bluetooth device that is detected is recorded along with a time-stamp. Thus, a MAC address detected at more than one Bluetooth site represents a unique Bluetooth device which traveled from one site to the next, and its travel time may be determined by calculating the difference in the time-stamps.

2.3 Bluetooth Travel Time Measurement Methods

Research in the field of Bluetooth technology for travel time measurement has been developed substantially in recent years, and several vendors have developed Bluetooth products to provide travel times to their clients more effectively and inexpensively. The studies reported in this summary exemplify the development of Bluetooth technology in traffic monitoring.

2.3.1 Accuracy and Cost

Bluetooth technology is being increasingly utilized by government agencies, consulting firms, and researchers as an inexpensive and accurate method of measuring travel times. Wasson et al. [40] conducted two different field tests in Indianapolis on U.S. 31 and I-69 in early 2008 which proved the feasibility of matching MAC addresses to report travel times. A study was conducted in Oregon along a two mile segment of Tualitin-Sherwood Road to determine changes in travel time and travel time variability as a result of a signal timing change [41]. Six Bluetooth readers were used to show that both metrics were improved. Martchouk and Mannering [42] used Bluetooth units to analyze travel time reliability for the Indiana DOT along Interstate 69 in Indianapolis. It was determined that Bluetooth technology was effective in measuring travel times.

The performance of Bluetooth technology in estimating travel times has been compared to floating car methods and radio-frequency identification (RFID) as an accurate and cost-effective alternative [7, 43-46]. In 2010, Schneider IV et al. [43] completed a study comparing Bluetooth to floating car methods. Several tests were conducted to measure the performance of Bluetooth on both interstate highways, urban arterial roads, and state highways. The number of matches for the arterial tests was much lower than the interstate tests. To increase the number of

Bluetooth matches, which is the number of MAC addresses detected at more than one site, it is suggested that Bluetooth stations should be installed one to two miles apart [43]. A MAC address detected at only one site may not be used to produce a travel time. An important finding of this study, supporting the potential usefulness of utilizing Bluetooth for real time travel time studies, is that the travel times produced by the Bluetooth method matched those from the floating car methods.

Kim et al. [44] compared the use of Bluetooth readers to TRANSMIT (RFID) readers and INRIX, a traffic information system that reports real-time data. The systems were tested along I-287 in New Jersey and detected instrumented probe vehicles as ground truth. The Bluetooth sensors produced the most accurate travel times as compared to the RFID readers and the INRIX system, matching the ground truth more closely. This further suggests that Bluetooth technology can be used to provide accurate travel times.

In addition to the advantages in accuracy, a major advantage of using Bluetooth to measure travel times is its relatively low cost. Bradley [7] quotes Phil Tarnoff, CEO of Traffax Inc., as stating, “We estimated the cost per travel-time data point of the Bluetooth data was just 1/300th of the cost of comparable floating car data.” A study completed by Young [45] estimates that Bluetooth may be 500 to 2500 times more cost-effective than floating car data collection in terms of the number of data points produced. A PennDOT study concluded that the cost of TrafficCast’s BlueTOAD equipment would be one-third of the costs associated with EZPass equipment, which is an RFID toll tag reader system [46]. Bluetooth’s comparably low-cost may make it an attractive alternative to other travel time monitoring methods.

2.3.2 Type and Placement of Bluetooth Readers

The type of Bluetooth antennas and their placement impacts the quantity and quality of Bluetooth data collected. Porter et al. [47] concluded that vertically polarized antennas with gains between 9 and 12 dBi are good candidates for Bluetooth-based travel time data collection systems. Malinovskiy et al. [48] found that out of several different configurations of Bluetooth sensors, the best detection rate was produced when two omni-directional antennas were placed at the same location on opposite sides of the road. The findings of this study suggest that multiple readers at one site may yield a greater number of detections of Bluetooth devices.

The effect of vertical placement of Bluetooth sensors also plays a role in the performance of Bluetooth sensors in detecting MAC addresses. A study conducted along I-65 in Indianapolis, Indiana, tested the performance of five Bluetooth sensors placed at varying heights between 0 feet and 10 feet [49]. The results show that the readers at 7.5 feet and 10 feet produced similar results. The other three readers, however, performed much more poorly. Further research is required to determine if an optimal height may be generally determined or specific to each site.

2.3.3 Outlying Data and Filters

As with any travel time measurement method, sources of error exist and outlying data points must be addressed to ensure that accurate travel times are reported. Errors may appear in Bluetooth travel time measurements on arterials as a result of signal delay and non-uniform traffic flow [50, 51]. The 10.24 seconds required to complete the Bluetooth inquiry process may introduce a major source of error and may result in inaccurate travel times, though this error decreases as the distance between Bluetooth stations increases [48, 52].

In the same way, the size of Bluetooth detection zones also introduces error. Figure 1 presents a graphic of what a Bluetooth detection zone may look like. Large detection zones, i.e. 330 feet for Class 1 radios, on short corridors may result in inaccurate travel time reporting because Bluetooth devices may be detected at any point within the detection zones. However, Malinoskiy et al. [48] recommend that larger detection zones are desirable, because although there is a loss in accuracy of travel time measurement, a higher matching rate is produced which improves the sample size and reduces random error rates.

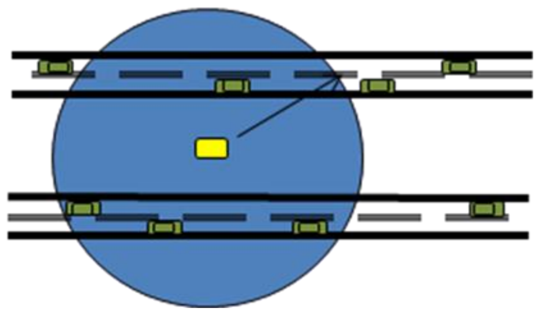


Figure 1. Example of Bluetooth Detection Zone
Source: Traffax, Inc.

Another source of error is the presence of outliers, which are Bluetooth travel times that do not represent actual conditions. Freeway travel time data must be filtered for the following: vehicles exiting the freeway and returning to the freeway between two stations; vehicles which temporarily stop on the shoulder or are traveling slowly due to repair requirements; and vehicles which are recorded at the upstream station, missed at the following station, and then detected at the second station traveling in the opposite direction later on in the day [42]. The former source of outlying data was also observed by Schneider et al. [43].

Nelson [53] suggests that filters may be created which define minimum and maximum travel times, though this may prove to be problematic on road segments which experience high variability in travel times throughout the day. Outliers that may appear on arterial roads include pedestrians and cyclists with detectable Bluetooth devices and buses which may have multiple Bluetooth devices onboard [48]. Roth [54] presents a time-series approach of removing outlying data points from Bluetooth data. The study recommends that a modified Z-test approach be used to identify outliers because it is computationally inexpensive and only a single iteration is required.

2.3.4 Sample Size and Match Rates

The sample size of data is critical in providing accurate and up-to-date travel times. Bluetooth devices that are detected at both stations are a sample of the Bluetooth devices that are detected, which is a sample of the population with discoverable Bluetooth devices [50]. The match rate is defined as the percentage of Bluetooth devices which are detected at two or more Bluetooth sites out of the total traffic volume. The detection rate is the fraction of Bluetooth devices that are detected out of the total traffic volume. The population with discoverable Bluetooth devices is a sample of the total traffic volume.

An early test of Bluetooth travel time measurement produced match rates of 1.2 percent and 0.7 percent [40]. Neal Campbell, CEO of TrafficCast, is quoted by Bradley [7] as stating that BlueTOAD, TrafficCast's Bluetooth-based traffic monitoring system, achieves match rates in the 3 to 6 percent range. An evaluation of the BlueTOAD system captured approximately 4 percent of the traffic stream [46]. Kittelson & Associates, Inc., obtained match rates of 3 percent and 4 percent during the AM peak and PM peak respectively during a 2009 Bluetooth study [41, 55].

Haghani and Young [56] obtained match rates ranging from 2 percent to 5.5 percent during a validation test of the University of Maryland's Bluetooth system in six eastern states. A one-hour study conducted by Wang et al. [57] resulted in 31 matched devices out of 1427 vehicles that traveled the study corridor, obtaining a 2.2 percent match rate. These match rates are sufficient in producing accurate travel times according to a study conducted in 2010 [46]. For roadways of 36,000 average annual daily traffic (AADT), 9 matched pairs per 15-minutes, 36 matched pairs per hour, and 864 matched per day (2 percent match rate) are sufficient for providing accurate travel time estimates [46]. Roadways with smaller AADT require a larger percentage.

It is difficult to determine the Bluetooth penetration rate, which is the percentage of vehicles which contain discoverable Bluetooth devices, because this value may be specific to the area and may change throughout the day. For example, more affluent areas may be characterized by a greater number of Bluetooth devices per vehicle. Still, a few studies suggest percentages with which to compare match rates. Asudegi [58] assumes that 3 to 5 percent of normal traffic streams contain discoverable Bluetooth devices. Haghani and Young [56, 59] approximate that 5 percent of vehicles contain a discoverable Bluetooth device in the United States. Hainen et al. [60] estimate that 7 to 10 percent of passing vehicles have detectable Bluetooth devices. Finally, Brennan Jr. et al. [49] suggest that 5 percent to 10 percent of the vehicle population has discoverable MAC addresses. Roadways that are traveled by more Bluetooth-carrying drivers are good candidates for Bluetooth travel time studies.

2.3.5 Further Application

In addition to reporting travel times, Bluetooth data may be used to supplement the data recorded by traffic management systems. Also, Bluetooth systems may be used in other applications including work zone studies, origin-destination studies, and traffic volume studies.

Petty and Kwon [61] proposed the fusing of Bluetooth data with ITS data to provide a more robust dataset in which performance measures can be calculated accurately and cost-effectively. For instance, the authors suggest that Bluetooth data may be combined with loop detector and toll tag reader data in areas where loop detectors and toll tag infrastructure already exist.

Bluetooth may also be used to collect data on work zone travel time delay, as was the case on I-65 in northwestern Indiana in 2009 [62]. Portable and semi-permanent installations of Bluetooth were implemented during the repaving of the interstate. Haseman et al. [62] suggest that the travel times produced may be displayed in real-time using message boards and websites.

In addition to travel time monitoring, Bluetooth systems may also be used to estimate origin-destination (OD) pairs [8, 40, 60]. Barceló et al. [8] tested the potential of Bluetooth in dynamic OD estimation in May and June of 2009. Six Bluetooth sensors were deployed on on-ramps and off-ramps along a 40 kilometer segment of the AP-7 Motorway in Barcelona, Spain. Hainen et al. [60] used Bluetooth technology to determine route choice after an Indiana bridge was closed for repair. Four different alternative routes were determined and instrumented with Bluetooth sensors. It was observed that the majority of drivers did not use the official detour. The results were explained by the Bluetooth travel time data which found that the travel times along the detour were longer than the primary route.

Nelson [50] suggests that although Bluetooth traffic monitoring systems cannot collect traffic volumes, detection rates may be compared to traffic volume counts collected via another method to establish a baseline for the study location. As a result of a study of Bluetooth travel time measurement on arterial roads, Schneider et al. [43] suggest that the number of MAC address matches is proportionate to the traffic volume traveling the roadway. This study suggests that the proportion of Bluetooth devices per vehicle is not expected to vary from daytime to nighttime.

2.3.6 Summary

Several recent studies have been conducted concerning the use of Bluetooth technology in travel time monitoring. Proven to be accurate and cost-effective compared to other travel time technologies (probe vehicle studies and RFID technology), Bluetooth has the potential to become a desirable alternative travel time data collection method. As mentioned by previous studies, the type and placement of Bluetooth readers can greatly affect the quality and quantity of the data output. Sources of error include vehicles departing and entering within a study segment, missed detections, and the variability of detection of a Bluetooth device within a detection zone. However, filters may be developed to remove the outlying data points. Additionally, Bluetooth technology has been proven to yield sufficient sample sizes to report travel times accurately. This study seeks to provide a better understanding of Bluetooth in travel time monitoring and to provide recommendations for future Bluetooth field deployments.

CHAPTER 3: METHODOLOGY

This chapter describes the methodology which may be used to design a Bluetooth travel time field experiment. The objective is explained in Section 3.1. The general concept of measuring travel times using Bluetooth technology is discussed in Section 3.2. Also included in Section 3.2 are descriptions of the independent variables, dependent variables, and data outputs that may be associated with Bluetooth-based travel time measurement.

3.1 Objective

It cannot be guaranteed that the MAC address of every Bluetooth device in passing vehicles that come within range of a Bluetooth reader will be detected, even if the device is in discovery mode. For instance, it is possible that the 10.24 second inquiry time required to find a particular Bluetooth device will exceed the time the vehicle is within range; thus the device MAC address will not be detected. Another potential issue is that given the location of the device in the vehicle, the signal may experience sufficient interference which will cause the device to not be detected. The objective of this research is to gain an understanding of how the placement of a Bluetooth reader influences the likelihood of a Bluetooth device being successfully detected given the limited time a vehicle remains in the potential detection zone, to study the potential influence of the location of the Bluetooth device in the vehicle, and to better understand how Bluetooth data must be analyzed and filtered to provide accurate travel times.

3.2 Field Measure of Travel Time Using Bluetooth

To produce travel times using Bluetooth, at least two sites which are positioned a known distance apart must be equipped with Bluetooth readers. The readers detect a subset of the MAC addresses of Bluetooth devices traveling through the detection range of the readers. Time-stamped detections of the same MAC address at both sites allow for an estimated travel time for the vehicle in which the Bluetooth device is located by calculating the difference in time-stamps recorded at the two sites. Given a sufficient sample of vehicle travel times, an average segment travel time may then be determined with accuracy increasing as the sample size increases.

3.2.1 Independent Variables

The independent variables which must be determined before deployment of Bluetooth readers include: the location and number of sites, which define the lengths of the study segments; the horizontal and vertical placement of readers; the type and number of readers; and the start time, end time, and duration of the study period where installation is to be temporary. These variables may directly influence the number of detections per site and over the entire study network, as well as the match rate, which is defined as the number of unique Bluetooth MAC addresses read at multiple sites out of the total traffic volume [46]. It is important to note that the location of the device in the vehicle may also influence the likelihood of the device detection. While this is not a variable that is typically controllable as part of a Bluetooth data collection effort, this research utilized several probe vehicles which are introduced into the traffic stream with known Bluetooth device locations.

3.2.1.1 Bluetooth Sites

For use in arterial travel time studies, stations equipped with Bluetooth readers are commonly deployed at mid-block locations to avoid biasing the travel time data with oversampling of Bluetooth devices in vehicles that queue at intersections. However, permanent installations may require housing Bluetooth units within signal controller cabinets, and thus closer to the intersection, to prevent vandalism, theft, or damage caused by weather conditions. The processing of the Bluetooth data must be adjusted to any site-specific conditions.

As seen, a minimum of two Bluetooth stations must be established to produce travel times. However, the total number of stations in the system depends on the needs of the user and the typical trip lengths. In contrast to freeway travel time studies, arterial roads typically experience a significant number of vehicles departing and entering the roadway from cross-streets over relatively short distances. Establishing longer study segments on arterials may adversely impact the sample size of matched MAC addresses at a pair of Bluetooth stations. While not considered directly in this study, the percentage of vehicles traveling the full segment length between Bluetooth detectors is an important consideration in setting reader locations and should be considered in the development of a system deployment plan. In addition, arterial roads are also much more likely to experience trip-chaining, where drivers may stop for errands or other purposes between detections at Bluetooth readers. This produces a travel time that is not representative of the actual conditions of the arterial. Given these issues, Schneider IV et al. [43] recommend a study segment length of one to two miles for arterial roads. However, a field test on a roadway with major cross-streets and driveways may require a shorter study length.

3.2.1.2 Bluetooth Readers

Both the lateral and vertical placement of Bluetooth readers may affect the number of discoverable Bluetooth devices that the readers will detect. As demonstrated by Brennan Jr. et al [49], vertical placement of Bluetooth readers should be prioritized over the offset from the road.

Most studies have placed only one Bluetooth reader at each site to avoid interference between two readers. Brennan et al. [49] separated the Bluetooth readers in their study by 500 feet to ensure no Bluetooth radio interference. However, a study completed by Malinovskiy et al. [48] determined that one can obtain substantially larger detection rates if two Bluetooth readers are placed at one site. Signal interference was not studied as a part of their research. In a pedestrian study conducted in 2006, O'Neill et al. [63] simultaneously used three Bluetooth readers to increase the likelihood that a passing pedestrian with a discoverable Bluetooth device would be detected. This study found that if 20 pedestrians carrying Bluetooth devices simultaneously traveled through the detection zone of a Bluetooth reader, only 60% of the devices could be recorded [63]. This research suggests, then, that placing more than one reader at a single site may produce a more robust dataset of detected MAC addresses.

3.2.1.3 Study Period

For temporary deployments, several time variables must be determined in the development of a field deployment plan including the length of the study period, the day of the week or time of year, and the time of day. Non-recurring incidents in the area should also be noted. As traffic volume increases, it may be expected that sample size will also increase. Thus, for low-volume roadways, longer sampling periods will be required than for higher-volume areas. The length of the data collection period is a direct function of the desired sample size (based on desired statistical significance) and the assumed percentage of vehicles that will be sampled. As seen in previous studies two to six percent of vehicles are commonly sampled [7, 41, 46, 56, 57].

3.2.1.4 Probe Vehicles

In this research, probe vehicles equipped with GPS devices (which log global coordinates during travel), Bluetooth-enabled GPS devices, and other Bluetooth devices with known MAC addresses are utilized on the study segment to provide ground truth travel time data. The data may then be compared to the collected Bluetooth data. An additional method by which ground truth data may be collected is the use of observers tasked to ride in the probe vehicles to record the exact times at which the vehicles pass the Bluetooth stations.

Where multiple lanes exist, probe vehicles may also be assigned to a specific lane to maintain a minimum distance from each Bluetooth reader as they pass, allowing the comparison of the detection rate of devices located within probe vehicles driving in different lanes.

3.2.1.5 Video Data Collection

To determine detection rates and match rates, traffic counts at the sites must be obtained. In this effort, the corridor was video-recorded during the data collection, allowing for post-analysis collection of volume data. Using the traffic volumes and number of MAC addresses detected, detection rates may be studied.

3.2.2 Dependent Variables and Data Output

The primary dataset obtained from a Bluetooth travel time study is the time-stamped MAC addresses from each Bluetooth reader. In addition to the time-stamp of each detection, the location of the reader should also be recorded. An example output for one reader is shown in Table 1. Additionally, each Bluetooth unit may be outfitted with a GPS device to log its latitudinal and longitudinal coordinates.

Table 1. Example Output from a Single Bluetooth Reader

Time	Month	Day	Year	MAC Address
17:08:19	Jan	21	2011	00:30:01:40:08:6D
17:09:20	Jan	21	2011	00:30:01:40:08:4D
17:09:21	Jan	21	2011	00:30:01:40:08:4D
17:12:23	Jan	21	2011	00:1E:B2:45:CF:00
17:13:12	Jan	21	2011	00:0D:B5:38:B9:22
17:13:13	Jan	21	2011	00:30:91:40:08:3D

Due to the nature of Bluetooth detection zones, devices traveling through these zones may dwell longer than a single detection cycle iteration and may be reported more than once. To ensure accurate travel times, a consistent convention must be established. This study utilized first-to-first detections to calculate travel times.. Future research efforts will consider the accuracy of travel time measurements using different detection instances, such as last-to-last, averages, etc.

The GPS loggers provide ground-truth travel times with which to compare travel times produced by the Bluetooth sensors. Travel times may be calculated by first determining the GPS locations of the Bluetooth stations. By determining the times at which the probe vehicle traveled past the Bluetooth station using the GPS data and calculating the difference in times, ground truth travel times may be produced.

Traffic volumes at each site will allow for the calculation of a detection rate at each site and a match rate between pairs of sites. Traffic volumes may also be compared to the number of individual detections and the number of unique MAC addresses detected.

3.3 Summary

Chapter 3 outlines a methodology which may be used to develop a Bluetooth travel time field study. The independent variables to be determined before Bluetooth deployment include: the location and number of sites; the type, number, and placement of Bluetooth readers; the temporal length of study; a method to produce ground truth travel times; and a method to obtain traffic volume counts. The desired output of a Bluetooth study are time-stamped detections of MAC addresses which may be matched across Bluetooth readers to calculate travel times. Chapter 4 describes how this methodology was used to develop the field test on Spring Street.

CHAPTER 4: EXPERIMENTAL DESIGN

This chapter describes in detail the preparation and data analysis of the field experiment conducted on Spring Street in Atlanta, Georgia, on January 21, 2011. Section 4.1 explains the rationale behind the selection of the sites and their characteristics. Section 4.2 describes the details of the study period. Section 4.3 describes the design of the Bluetooth stations deployed at each site. Sections 4.4 and 4.5 illustrate how video cameras and probe vehicles were used to provide data for ground truth comparison and for the calculation of critical performance metrics such as detection rate and match rate. The protocols for using Bluetooth adapters, netbooks, Ubuntu, and PERL scripts to create a Bluetooth MAC address reader are presented in this chapter, as well as the details of the field deployment. Further details are provided in Appendix A and Appendix B.

4.1 Site Locations and Study Segment

A 0.9-mile segment of Spring Street in Atlanta, Georgia, was selected as the study corridor on which MAC addresses would be collected. Spring Street is a one-way, four-lane arterial with an estimated AADT of 12,960 [64]. Spring Street is located in the midtown area of Atlanta, having generally urban characteristics defined by multi-story commercial and residential developments, parking lots, and numerous access and egress points to roadside developments. Figure 2 presents a map of the study segment [65].

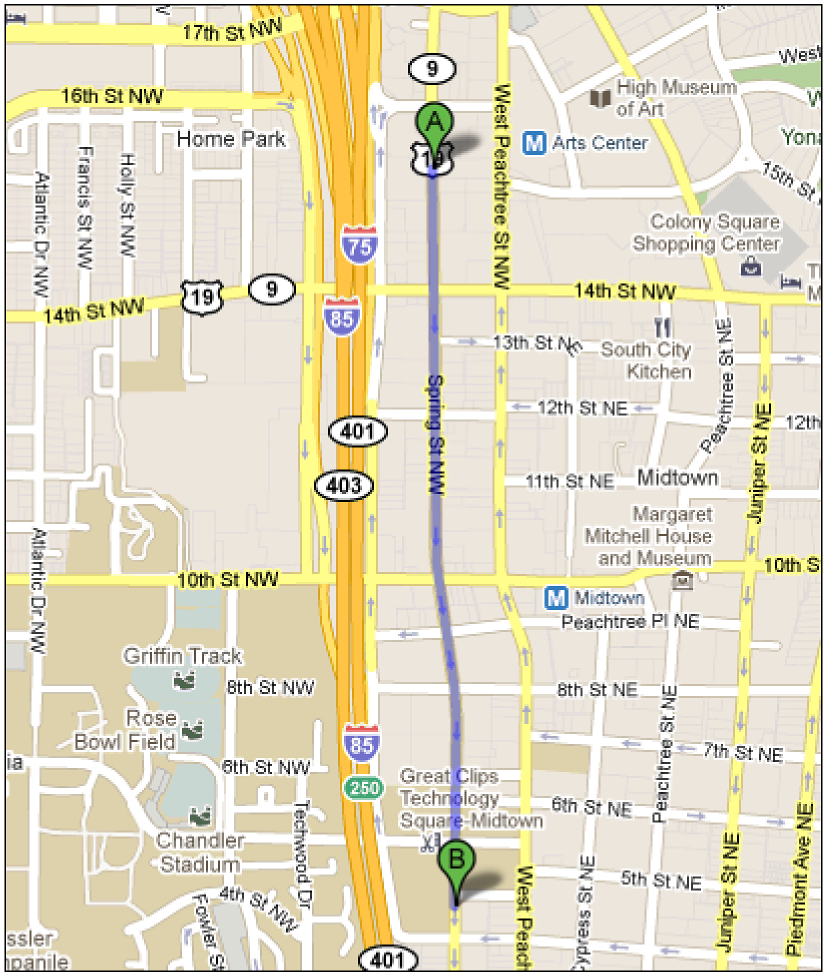


Figure 2. Map of Spring Street Study Segment
Source: Google Maps, http://maps.google.com/, accessed March 30, 2011

Two sites were selected based on safety, accessibility, offset from the road, minimal obstacles, and efficiency of potential probe vehicle routes. The first Bluetooth station was positioned in the Trump Towers Surface Parking Lot (location A on Figure 2) and the second Bluetooth station was positioned on the brick area in front of the Crum and Forster Building (location B on Figure 2). Three signalized cross-street intersections exist between these two sites 14th Street (4-lane, two-way, AADT of 17,060), 10th Street (4-lane, two-way, AADT of 22,430), and 5th Street (2-lane, two-way, AADT estimate not available although likely on the order of 5,000 to 10,000) [64]. Several smaller cross-street intersections also exist (13th Street, 12th Street, Peachtree Place, 8th Street, Abercrombie Place, Biltmore Place, and Armstead Place) as well as numerous driveways with surface parking lots, parking garages, and adjacent properties.

The parcel of land originally proposed for the construction of Trump Towers is now a surface parking lot operated by the Central Parking System. Located at 1252 West Peachtree Street, the parking is located between 16th Street and 14th Street and is bordered by Spring Street and West Peachtree Street. Its GPS coordinates are 33.78864° N, 84.38918° W. This site, which is shown in Figure 3 [65], was selected because very few vehicles occupied the parking spaces closest to the road, the Bluetooth readers could be placed sufficiently close to the roadway (within 30 feet), and no equipment would obstruct the sidewalk. The general manager of the Central Parking System permitted the use of space within the parking lot for this study.

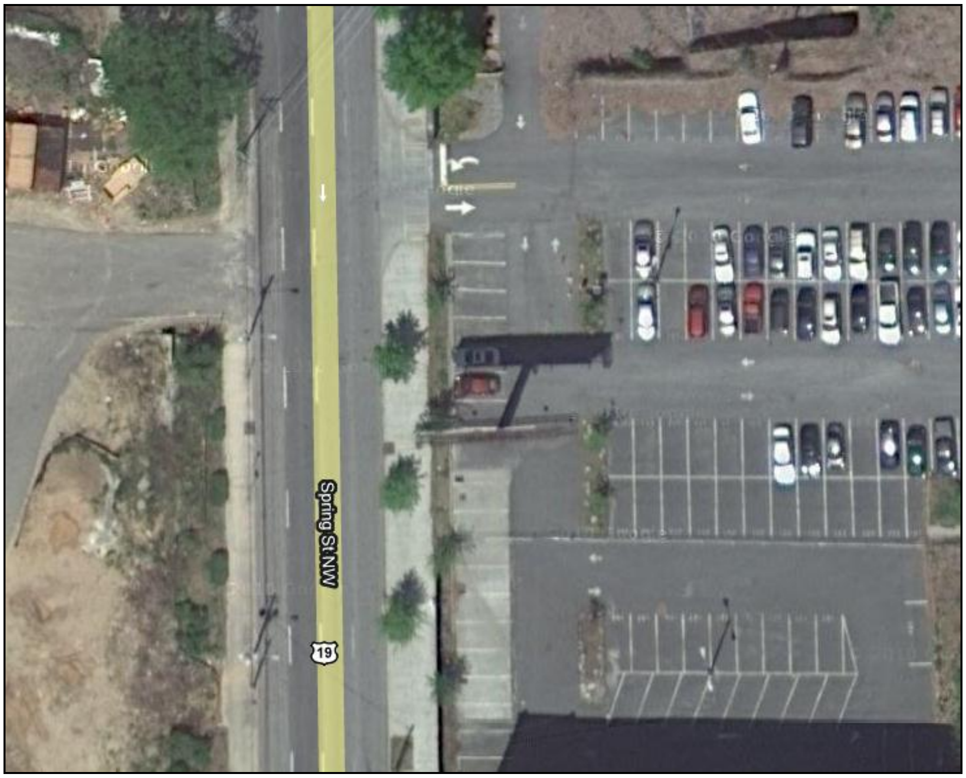


Figure 3. Map of Site 1 (Trump Towers Surface Parking Lot)
Source: Google Maps, http://maps.google.com/, accessed March 30, 2011

The Crum and Forster Building is located at 771 Spring Street between 5th Street and 4th Street (which turns into Williams Street). This site is shown in Figure 4 [65]. Its GPS coordinates are 33.77561° N, 84.38862° W. Located adjacent to Georgia Tech's Barnes & Noble Bookstore, this site has higher pedestrian activity than the other site creating the potential for the detection of extraneous MAC addresses from devices carried by pedestrians and customers within the bookstore. However, the Bluetooth station was more than 330 feet away from the bookstore and from the major pedestrian thoroughfare (5th Street), minimizing these potential interferences. The site benefited from the existence of a large, flat area in front of the building. The size of the area allowed for matching the reader offset from the roadway at this site with the other site, limiting potential bias that could be associated with different offsets. In addition, no obstacles existed between the site and the roadway. Permission to place the equipment at this site and conduct the data collection was obtained from the President and Chief Operating Office of the Georgia Tech Foundation.

Figure 4. Map of Site 2 (Crum and Forster Building)
Source: Google Maps, http://maps.google.com/, accessed March 30, 2011

4.2 Study Period

The field experiment was conducted on Friday, January 21, 2011, from 3:00 PM to 6:30 PM. Friday afternoon proved to be an ideal study period because of the changes in traffic pattern from free-flow to heavy congestion during the study period.

4.3 Bluetooth Reader Deployment

The Bluetooth readers consisted of Bluetooth adapters connected via USB cables to netbooks which ran PERL scripts to continuously detect and record MAC addresses of detectable Bluetooth devices. The Bluetooth adapters were attached to large tripods while the netbooks were contained within plastic bins on the ground. Four Bluetooth readers were deployed at each site, totaling eight readers in all. Section 4.3.1 and Section 4.3.1 briefly describe the specifications of the Bluetooth adapters that were used and how MAC address data were collected. A more detailed discussion of the Bluetooth specification and instrument setup may be found in Appendix A. Section 4.3.3 explains the variable heights aspect of this study, and Section 4.3.4 describes the offset of the stations from the roadway.

4.3.1 Bluetooth Adapters

This research utilized IOGEAR USB Adapters with Enhanced Data Rate (model number GBU321). These Class 1Bluetooth adapters have an ideal wireless range of up to 330 feet. The same adapter type was used for each Bluetooth reader to maintain consistency.

4.3.2 Netbooks, Ubuntu, and PERL Scripts

Further explained in Appendix A, MAC addresses were detected and logged using the Bluetooth adapters, USB cables, netbooks running Ubuntu (a Linux-based operating system), and scripts written in PERL. The PERL scripts enabled the Bluetooth adapter to continuously scan for other Bluetooth devices and log their time-stamped MAC addresses upon detection. The data were output to log files on the local netbook. After the completion of the experiment, the log files were manually transferred to centralize storage and compiled for data analysis.

4.3.3 Variable Heights

One goal of this study was to assess the impacts of antenna height on Bluetooth detection rates. Based on previous Bluetooth studies, 10 feet was used as a baseline. To accomplish the goal of better understanding the relationship between antenna height and detection rate, each Bluetooth station was outfitted with four Bluetooth readers: one at 7 feet, two at 10 feet, and one at 14.5 feet. Two Bluetooth readers were placed at 10 feet to compare the data collected by two Bluetooth readers placed in the same location at the same height. A height of 14.5 feet was the maximum for the tripod, and an extension beyond this point could not be achieved in a safe manner. Hence, 14.5 feet was chosen to be the maximum height instead of 15 feet as initially desired.

4.3.4 Offset from Roadway

The offset for both sites was controlled by Site 1, where a parking lot curb setback from the sidewalk became the controlling factor. Site 1 allowed for a minimum offset of 22.5 feet when the legs of the tripod were positioned flush against the parking lot’s curb (photos included in Appendix A). The tripod at Site 2 was set back the same distance from the roadway for consistency across sites. Given an expected ideal detection range of 330 feet for a Class 1 device, the selected offsets were deemed to be sufficient to detect Bluetooth devices across all four lanes of Spring Street.

4.4 Video Camera Data

Video camera data were collected for post-processing, allowing for the determination of traffic volumes during the study period. Video camera data were collected using two different methods. At Site 1, a high definition camera was mounted within a parked vehicle and recorded wide-angle video. Site 2 was already outfitted with a video detection system (described in Section 4.4.1) mounted on the roof of the Georgia Tech bookstore. Site 2 was also instrumented with a high definition camera at ground level during the experiment. The following sections describe the equipment and data collected.

4.4.1 Equipment

A Panasonic HDC-TM700 High Definition Video Camera was used to record video at Site 1 and Site 2. The video cameras were attached via suction mount to the windshield inside vehicles parked facing the roadway. In addition, at Site 2, a permanent vehicle detection camera was already in place and was used to record video data at Site 2. The video detection system hardware attached to the permanent cameras enables the creation of vehicle detection zones which automatically generates vehicle counts and speeds, as shown in Figure 5.

Figure 5. Permanent Vehicle Detection Camera View at Site 2

4.4.2 Traffic Volumes

One- and five-minute traffic counts were calculated for Site 1 by reviewing the video and performing manual counts. The video detection system provided time-stamped data points of each vehicle that traveled past Site 2. These data were aggregated into one- and five-minute traffic counts.

4.5 Probe Vehicles

Two probe vehicles instrumented with GPS data loggers continuously traveled the study segment to provide ground truth data for later comparison with the Bluetooth data. Each probe vehicle also had several Bluetooth devices with known MAC addresses, allowing for a paired data analysis of the calculated travel times from the Bluetooth reader and GPS data. In addition, the travel times of the detected Bluetooth devices placed within each probe vehicle and the GPS based travel times were compared to the travel times of matched non-probe vehicle devices.

The first probe vehicle driver was instructed to travel within the inside-lane, which is the lane closest to each Bluetooth station. Probe vehicle 1 completed 14 traversals of the study segment during the study period. The second probe vehicle driver maintained the outside-lane, the lane farthest from each Bluetooth station, and completed 20 traversals during the study period. Sections 4.5.1 through Section 4.5.3 describe the GPS logger devices and their data outputs. Section 4.5.4 details the Bluetooth emitter devices placed within each probe vehicle.

4.5.1 GPS Logger Devices

Three different types of GPS logger devices were positioned on the dashboard of each vehicle: a GlobalSat DG-100 GPS Data Logger, a GlobalSat BT-335 Bluetooth GPS with Data Logger, and a Qstarz BT-Q1000 Bluetooth GPS Travel Recorder. The two Bluetooth-enabled GPS loggers, the BT-335 and the BT-Q1000, contain Class 2 Bluetooth radios. As defined by the Bluetooth Special Interest Group [32], Class 2 Bluetooth radios must have a range of 10 meters (32.8 feet). GlobalSat advertises that the BG-335 has a range of 32 feet, while Qstarz states that the BT-Q1000 has a range of 15 meters (49.2 feet) [66, 67].

4.5.2 GPS Logger Travel Times

The DG-100 placed within probe vehicle 2 malfunctioned in the field and provided GPS data for only a fraction of the study period. It was seen that during the time-frame that the DG-100 was operational, its data corresponded well with the BT-335. The BT-Q1000 devices only recorded GPS coordinates every five seconds. Thus, the BT-Q1000 was not utilized for the calculation of ground truth data as the BT-335 provided data at a higher resolution of 1 Hz. The BT-Q1000 was able to serve as an additional Bluetooth device that could be detected in the probe vehicles. To allow for consistency between probe vehicle data collection methods, only the data from the BT-335 GPS loggers will be used as ground truth in this effort.

Thus, travel times were produced from the BT-335 GPS logger data by determining the times at which each probe vehicle passed Site 1 and Site 2, using Site 1's coordinates, 33.78864° N, 84.38918° W, and Site 2's coordinates, 33.77561° N, 84.38862° W. The difference in the times at which a probe vehicle passed each site was the travel time for that run for the probe vehicle.

4.5.3 GPS Dilution of Precision

The dilution of precision (DOP), or geometric dilution of precision, describes the extent to which GPS satellite geometry affects GPS precision. For example, GPS precision will be low if the signals received by a GPS device are from satellites that are in close proximity to each other in the sky. Lower DOP values indicate higher GPS precision. DOP may also be expressed in terms of horizontal position (HDOP), vertical position (VDOP), three-dimensional position (PDOP), and time (TDOP).

Low DOP values are critical for this study to ensure that the GPS loggers are recording accurate latitudinal and longitudinal coordinates. Table 2 shows the ratings associated with DOP values [68]. For this study, ratings of “excellent” or better were desired.

Table 2. Ratings for DOP Values

DOP Value	Rating
1	Ideal
2 to 3	Excellent
4 to 6	Good
7 to 8	Moderate
9 to 20	Fair
20+	Poor

DOP values are typically shown on the display screens of GPS devices. Unfortunately, the GPS loggers used for this study do not have display screens and they do not include DOP values in their output. Trimble’s Planning Software was used to retroactively estimate the DOP values for Site 1 and Site 2 during the study period. Although the software does not take into account large obstacles, i.e. the buildings and parking garages near Site 1 and Site 2, it offers a baseline from which one may estimate DOPs. The ranges of DOP values for Site 1 and Site 2 during the study period are shown in Table 3. Because Site 1 and Site 2 were located only 0.9 miles apart, the baseline DOP values outputted for each site were essentially the same.

Table 3. Estimated DOP Values for Site 1 and Site 2 during the Study Period

Site	DOP	HDOP	VDOP	PDOP	TDOP	# of Satellites
1 and 2	1.59 to 3.77	0.78 to 1.59	1.19 to 2.75	1.42 to 3.17	0.70 to 2.04	6 to 11

The PDOP and HDOP values are of utmost concern, because they indicate the dilution of precision for latitudinal and longitudinal coordinates. The values calculated by Trimble's Planning Software yields PDOP and HDOP values that are satisfactory for this study.

4.5.4 Bluetooth Emitter Devices

Three Sabrent Class 1 Bluetooth USB Adapters were placed within each probe vehicle as Bluetooth emitters. The MAC address of each emitter was identified before field deployment. To simulate typical placement of Bluetooth devices in random vehicles, within each probe vehicle a Bluetooth emitter was placed on the floor in front of the passenger seat, another was placed on the passenger seat, and another was attached to the dashboard. However, a Bluetooth emitter from each vehicle malfunctioned early on in the study period. The decision was made to keep emitters on the floors and on the passenger seats of the probe vehicles and to have two of the GPS loggers serve as the two Bluetooth emitters that were initially positioned on the dashboard. An extra Sabrent Bluetooth adapter was also placed on the seat of probe vehicle 1.

4.6 Summary

Chapter 4 describes in detail the characteristics of the field deployment and data collection methods for the Bluetooth test on Spring Street in Atlanta, GA, on January 21, 2011. A 0.9-mile segment was outfitted with two Bluetooth stations, each consisting of four readers placed at varying heights. Bluetooth data was logged using Ubuntu-operating netbooks and PERL scripts from 3:00 PM to 6:30 PM. Probe vehicles carrying GPS data logger devices and discoverable Bluetooth devices traversed the study segment to produce ground truth data and provide Bluetooth devices to be detected at each site. Finally, video cameras were used to collect data to collect traffic volume which was later used to determine detection rates and match rates for this study. The analysis of the data collected is presented in Chapter 5.

CHAPTER 5: RESULTS AND ANALYSIS

The results of the field experiment and subsequent analysis are presented in this chapter. Section 5.1 describes the main performance metric for each site: detection rate. The traffic volumes, variable height placement of the Bluetooth readers, and probe vehicle Bluetooth devices are also discussed in this section. Section 5.2 evaluates the Bluetooth system performance, describing the match rate while also comparing the travel times produced by the Bluetooth system to GPS logger ground truth travel times.

5.1 Site Performance Metrics

This study sought to accomplish several goals, one of which was to assess the optimal configuration of the Bluetooth equipment at a site. To optimize a configuration, data specific to each site were analyzed to measure the detection rates of the Bluetooth readers (placed at varying heights). A higher number of MAC addresses detected by one reader compared to another reader at the same site may suggest that antenna placement influences the likelihood of detecting Bluetooth devices. Additionally, the detection rates of the Bluetooth readers in detecting the probe vehicle devices were calculated.

5.1.1 Detection Rates of Unique MAC Addresses

The detection rate is the number of unique MAC addresses detected out of the total traffic volume over a period of time. While a single MAC address may be reported multiple times while a Bluetooth device is traveling through a Bluetooth reader's detection zone, it is the number of unique MAC addresses detected that indicates the reader's detection performance. It is assumed that the number of vehicles, other than the probe vehicles, making multiple round-trips on the study corridor during the study period is insignificant.To study the factors that may influence the detection rate, Bluetooth readers were placed at varying heights and Bluetooth devices with known MAC addresses were placed in two probe vehicles. Additionally, the relationship between volume and unique MAC addresses detected was studied, and an investigation was conducted concerning the interference between two Bluetooth readers placed within close proximity.

5.1.1.1 Traffic Volumes

To assess detection rates and match rates, traffic volume data are required for the study period. Two major cross streets, 14th Street and 10th Street, exist between the start and end of the study segment, so it was expected that traffic volumes at each site would differ substantially. A total of 5,876 vehicles (1,679 vehicles per hour) traveled past Site 1, while 3,964 vehicles (1,133 vehicles per hour) drove past Site 2. Figure 6 and Figure 7 show five-minute traffic counts for Site 1 and Site 2 respectively.

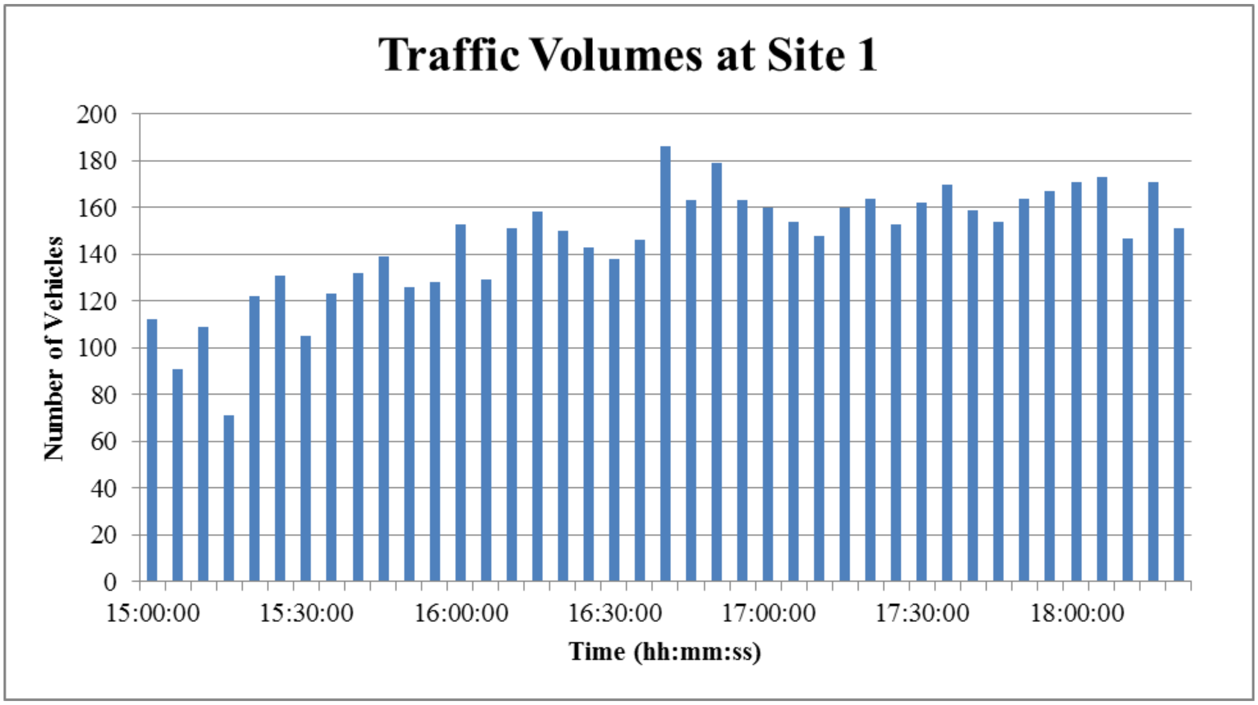


Figure 6. Five-Minute Traffic Volumes at Site 1 (Trump Towers Surface Parking Lot)

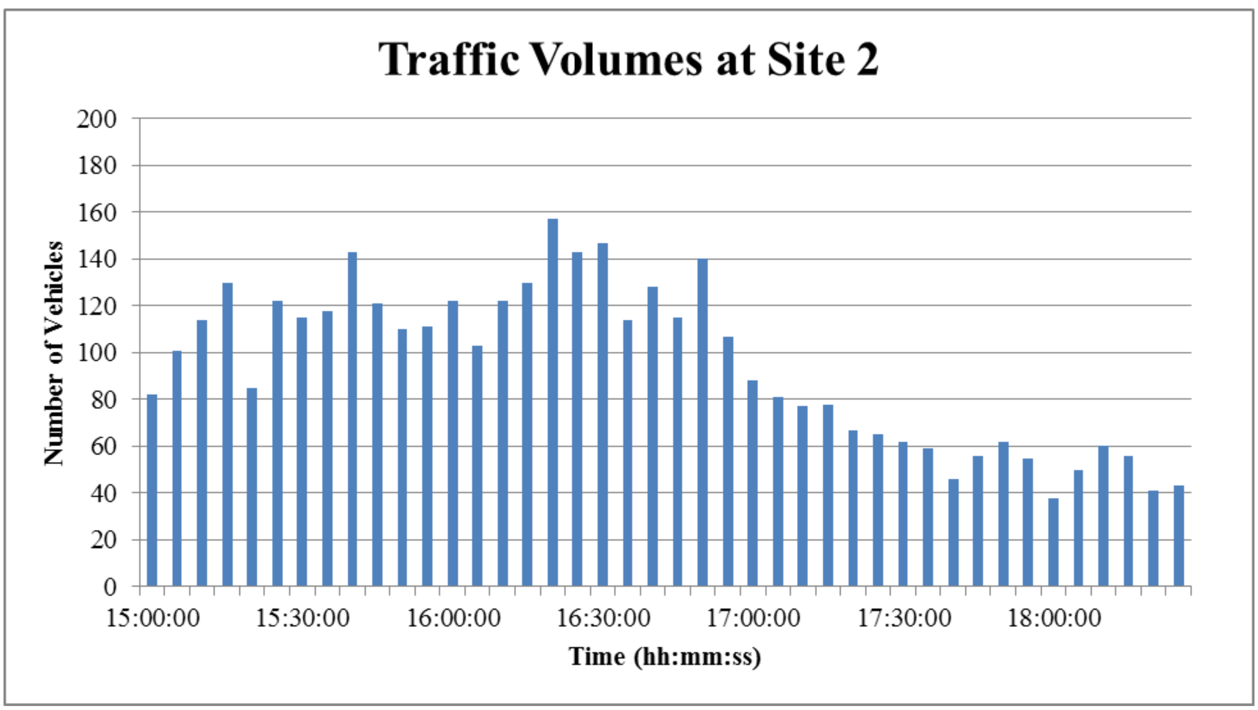


Figure 7. Five-Minute Traffic Volumes at Site 2 (Crum and Forster Building)

Traffic volumes at Site 1 increased steadily during the first hour and a half of the field test and maintained a flow rate of 150 to 170 vehicles every five minutes until the end of the study period. The queues from 14th Street extended into the detection zone of the Bluetooth station at Site 1 a number of times around 4:45 PM, but the site experienced free-flow traffic conditions for most of the study period. Site 2 is characterized by heavy levels of congestion and decreased throughput of traffic starting at around 5:00 PM. At this point, traffic queuing on Spring Street waiting to travel through the intersection with North Avenue, located 0.3 miles downstream, created long queues past Site 2 and beyond 5th Street. The road's capacity failed to be sufficient for the increased traffic volumes and the number of vehicles traveling past Site 2 decreased substantially.

5.1.1.2 Varying Heights

Four Bluetooth readers were placed at both sites at varying heights: one at 7 feet, two at 10 feet, and one at 14.5 feet. Two readers were originally placed at 10 feet to study the variance between two datasets produced by Bluetooth readers in the same location. However, the two pairs of readers at 10 feet are treated as two single readers for this study unless otherwise noted, because the number of MAC addresses detected by the readers at 10 feet were comparable to the single readers placed at 7 feet and 14.5 feet. This decision is further explained in Section 5.1.1.3.

The Bluetooth readers at Site 1 detected 261 unique MAC (4.44 percent of the total traffic at Site 1) during the field test. The Bluetooth readers at Site 2 detected 328 unique MAC addresses (8.27 percent of total traffic at Site 2). At each site, the MAC addresses detected consisted of those that were detected only by one reader, a pair of readers, or by all three. Figure

8 depicts the overlap of the detected unique MAC addresses across Bluetooth readers at the same site. Table 4 presents the number of unique and overlapping MAC addresses detected.

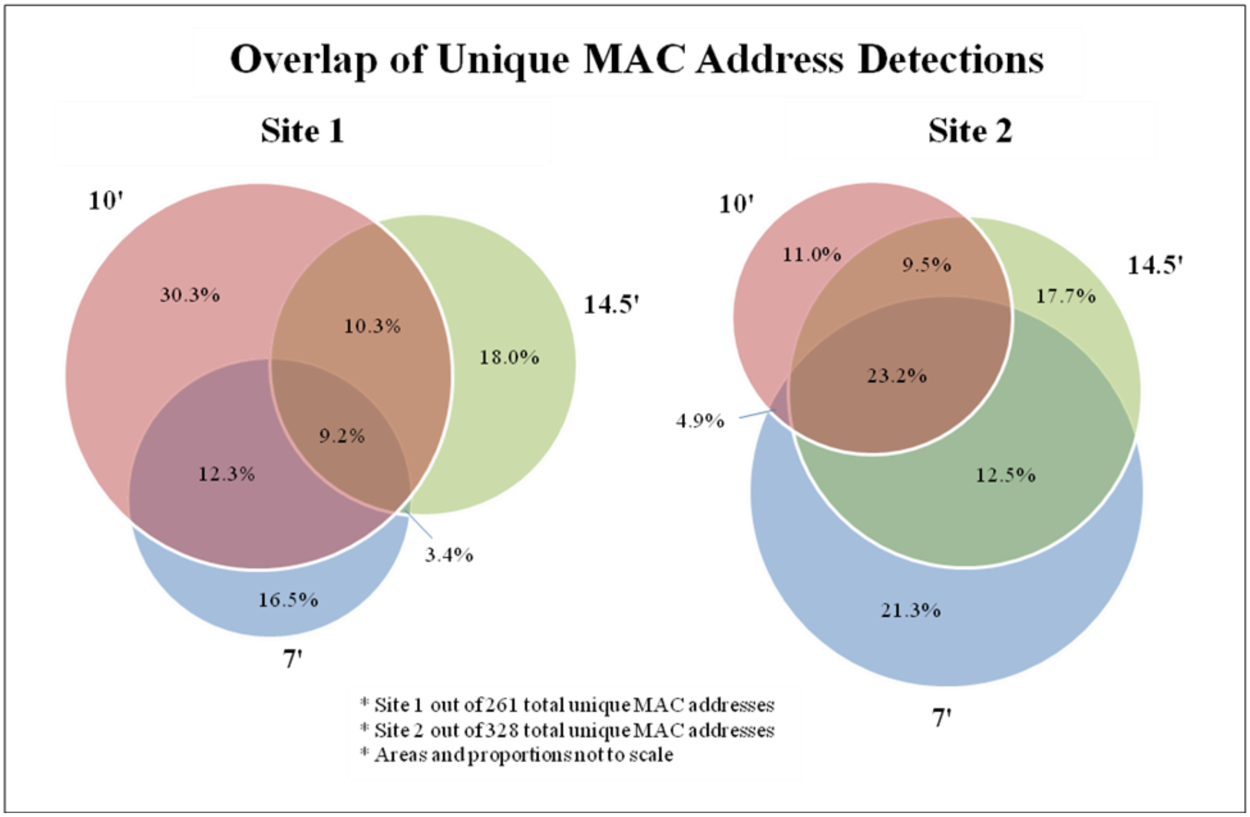


Figure 8. Overlap of Unique MAC Addresses Detected by Readers at Site 1 and Site 2

Table 4. Unique and Overlapping MACs Detected at Site 1 and Site 2

	Site 1		Site 2	
Bluetooth Reader	**MACs**	**Percentage**	**MACs**	**Percentage**
7' only	43	16.5%	70	21.3%
10' only	79	30.3%	36	11.0%
14.5' only	47	18.0%	58	17.7%
7' & 10'	32	12.3%	16	4.9%
10' & 14.5'	27	10.3%	31	9.5%
7' & 14.5'	9	3.4%	41	12.5%
All Heights	24	9.2%	76	23.2%
Total	261	100%	328	100%

The data show that at Site 1, the Bluetooth reader placed at 10 feet performed best, exclusively detecting 43 MAC addresses, detecting 32 MAC addresses also detected by the reader at 7 feet, and 27 MAC addresses also detected by the reader at 14.5 feet. This reader detected a total of 138 MAC addresses, compared to 84 and 83 for the Bluetooth readers at 7 feet and 14.5 feet respectively. However, the opposite was observed at Site 2. The Bluetooth reader at 10 feet performed most poorly, detecting 83 MACs compared to 127 and 130 detected at seven feet and 14.5 feet respectively.

Additionally, the overlap of MAC detection is surprising at Site 2, where there is only a 4.9 percent overlap in MAC detections between the Bluetooth reader at seven feet and the one placed at 10 feet. Approximately one in 10 MAC addresses detected at Site 1 were detected by all of the Bluetooth readers compared to approximately one in 25 MAC addresses at Site 2.

These findings support the potential that a greater detection rate may be achieved at one site if more than Bluetooth reader is utilized, as was observed by O'Neill et al. [63]. For example, at Site 1, the Bluetooth reader at 7 feet did not detect 58.6 percent of the MAC addresses which were detected by the other readers. Similar calculations yield missed detection rates of 37.9 percent for the reader at 10 feet and 59.1 percent for the reader at 14.5 feet. At Site 2, the missed detection rate for the Bluetooth reader at 7 feet was 38.1 percent, 51.4 percent for the reader at 10 feet, and 37.1 percent for the reader placed at 14.5 feet. These results suggest that a greater number of detectable Bluetooth devices will be detected by a Bluetooth site if the site contains multiple Bluetooth readers. This finding is likely critical to the deployment of a robust Bluetooth-based travel time system as the placement of a single optimal Bluetooth reader is likely a function of the site's characteristics. Thus, an optimal system is unlikely to be achieved where a single reader is placed at each location at the same pre-selected height. Multiple readers covering a range of heights increase the potential of achieving maximum possible detection at a site.

Further research is required to determine the factors affecting the detection rate of Bluetooth readers placed at different heights.

5.1.1.3 Two Readers at 10 Feet

During the initial stages of this study, it was decided to place two Bluetooth readers at the same height in one location to measure the variability in the number of detections and MAC addresses detected by each reader. However, after further investigation into literature concerning interference between Bluetooth devices and analysis of the datasets of the pairs of Bluetooth readers placed at 10 feet, the decision was made to treat the pairs as single readers due to the interference caused by their placement.

Bluetooth devices utilize adaptive frequency hopping to avoid interference with other wireless technologies, and in some cases, to avoid interference with other Bluetooth piconets [38, 69]. This frequency hopping is adaptive, meaning that if a Bluetooth device finds that certain frequencies out of the 79 frequencies are currently experiencing significant interference, it will categorize those frequencies as "bad" and continue to hop between the "good" frequencies. However, if both Bluetooth readers are constantly frequency hopping and experience transmission collisions on the same frequencies, both devices will not be able to effectively categorize "bad" frequency channels [69].

It was observed that the total number of MAC addresses detected by the four readers placed at 10 feet were comparable to the total number of MAC addresses detected by the two readers at 7 feet as well as the total number detected by the two readers at 14.5 feet. The data are presented in Section 5.2.1. Thus, the decision was made to treat the pairs of Bluetooth readers as single readers placed at 10 feet for each Bluetooth station. Figure 9 and Figure 10 show the overlap of MAC addresses detected by the Bluetooth readers placed at 10 feet at each site. The labels "first reader" and "second reader" were assigned to the Bluetooth readers at 10 feet to distinguish them when necessary. The Bluetooth reader pair at Site 1 detected 162 unique MAC addresses and the Bluetooth reader pair at Site 2 detected 159 unique MAC addresses.

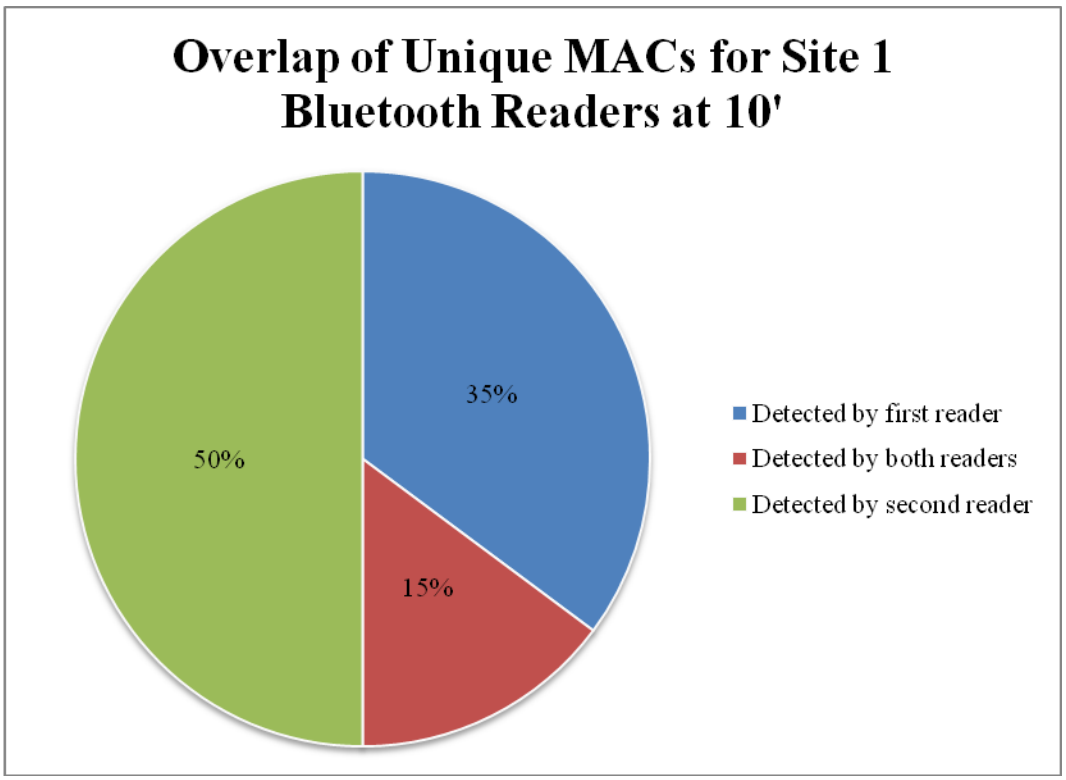


Figure 9. Unique MACs Detected by the Bluetooth Readers Placed at 10 Feet at Site 1

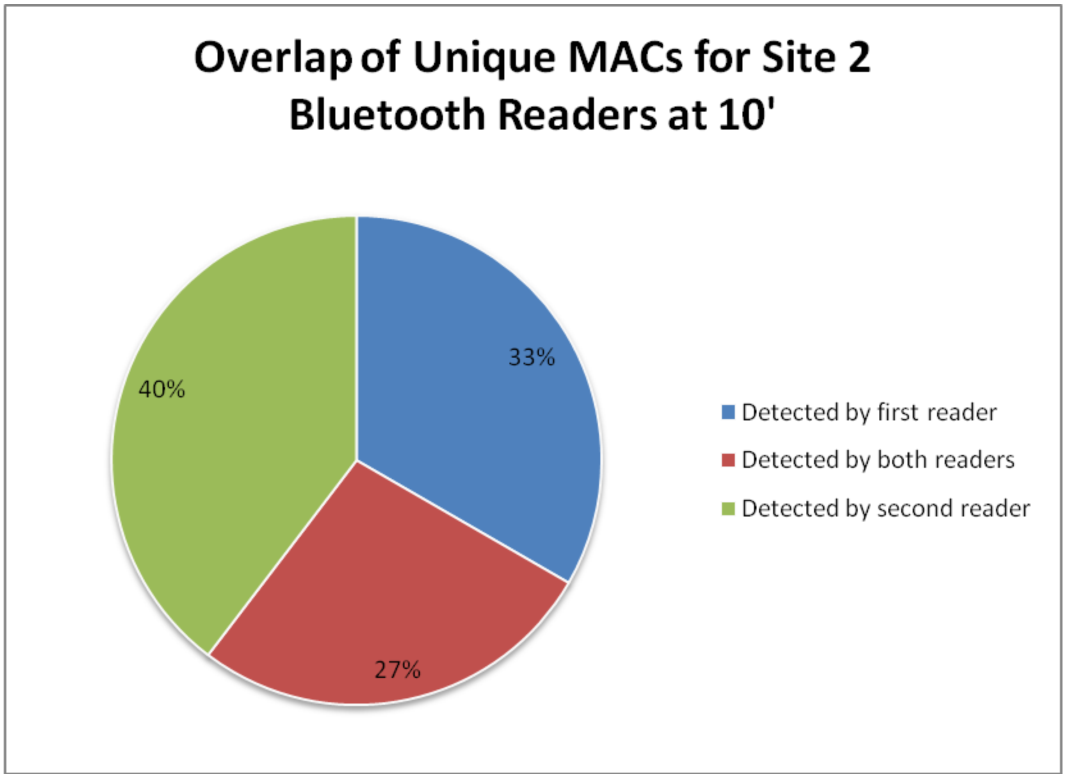


Figure 10. Unique MACs Detected by the Bluetooth Readers Placed at 10 Feet at Site 2

The relatively small overlaps suggest that at each site, the two Bluetooth readers at 10 feet are behaving as a single reader as a result of their close proximity and adaptive frequency hopping. Future experiments will seek to better determine the interference between the two closely spaced readers. For instance, a field test in which two Bluetooth stations are deployed is required to provide comparison data: one with a single Bluetooth reader at 10 feet and another with two Bluetooth readers at 10 feet. The two stations must be close enough to avoid the readers sampling from different sets of vehicles, but they must be sufficiently separated to negate the possibility of interference.

5.1.1.4 Detection Rates

The detection rates are calculated by dividing the number of detected unique MAC addresses by the traffic volume for a period of time. Several detection rates can be computed in the process: an overall detection rate for each Bluetooth reader, an overall detection rate for each Bluetooth station, and minute-by-minute detection rates for each Bluetooth station. Match rates between pairs of Bluetooth readers at the same height but at different sites are presented and discussed in Section 5.2.1. Table 5 shows the number of unique MAC addresses detected and the detection rate for each Bluetooth reader height, excluding the probe vehicle devices which will be discussed in Section 5.1.1.5. As previously mentioned, a total volume of 5,876 vehicles traveled past Site 1 and 3,964 vehicles passed Site 2. Table 6 presents the detection rates for Site 1 and Site 2, as well as the match rate, which is the number of MAC addresses detected at both sites. Because the traffic volume passing through the entire segment is unknown, Site 2's total traffic volume is used as a conservative estimate. Site 2's volume is a conservative estimate because the number of vehicles traveling through the entire study segment cannot exceed the number of vehicles which traveled past Site 2. The detection rates for each site in Table 6 are higher than those for each reader in Table 5 because the site detection rates are based on all of the unique MAC addresses detected at the site.

Table 5. Detection Rates for Each Bluetooth Reader Height

	Height	Unique MACs Detected[1]	Detection Rate
Site 1	7'	108	1.84%
	10'	162	2.76%
	14.5'	107	1.82%
Site 2	7'	203	5.12%
	10'	168	4.24%
	14.5'	206	5.20%

[1]Includes all MAC address detected at the given height. As individual MAC address may be represented at multiple heights.

Table 6. Detection Rates for Site 1 and Site 2

Site	Unique MACs Detected	Total Volume	Detection Rate
1	261	5876	4.4%
2	328	3964	8.3%
Both	71	3964[1]	1.8%

[1]A conservative estimate of vehicles traveling past both sites

It is seen that the Bluetooth readers at Site 2 obtained greater detection rates. This is potentially attributed to lower travel speeds and greater dwell times of vehicles in Site 2's detection zone. As the amount of time a Bluetooth device is within range of a Bluetooth station increases, its likelihood of being detected also increases. Consequently, a longer dwell time may result in a greater number of detections. Figure 11 and Figure 12 display aggregated five-minute traffic volumes, number of detections logged (includes MAC addresses that are logged multiple times while in detection range), and number of unique MAC addresses detected for Site 1 and Site 2 respectively.

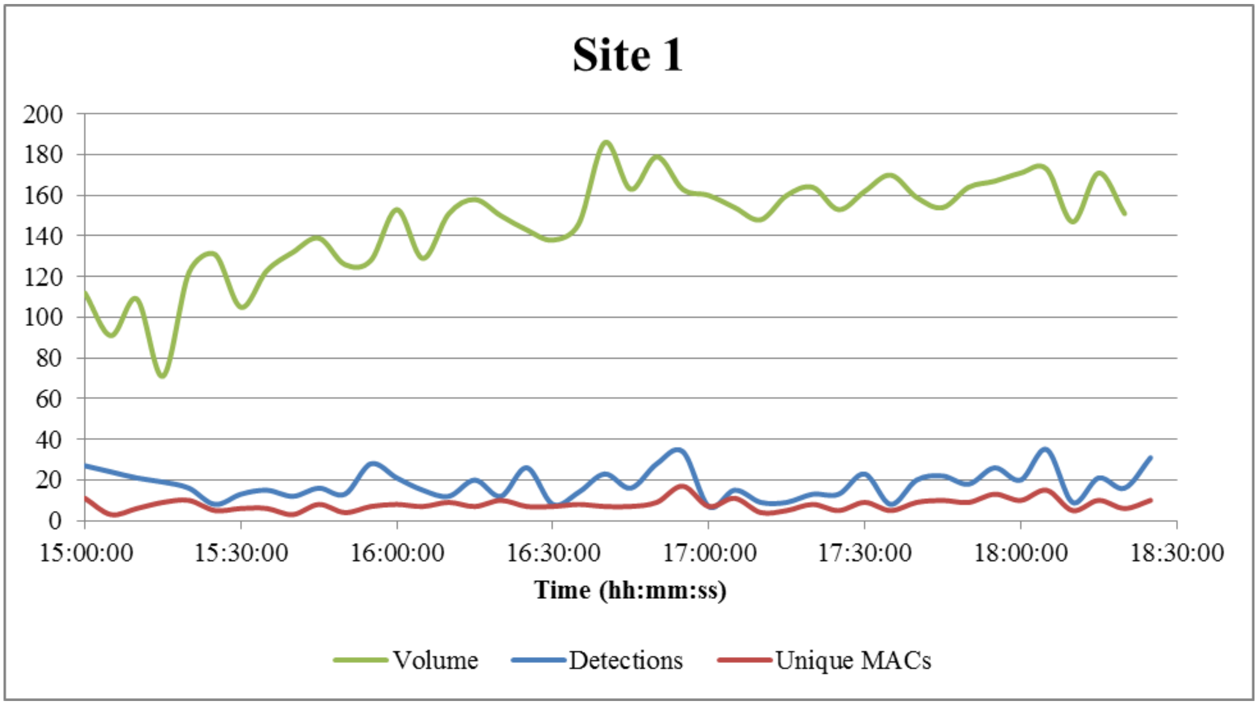


Figure 11. Traffic Volumes, Detections, and Unique MAC Addresses for Site 1

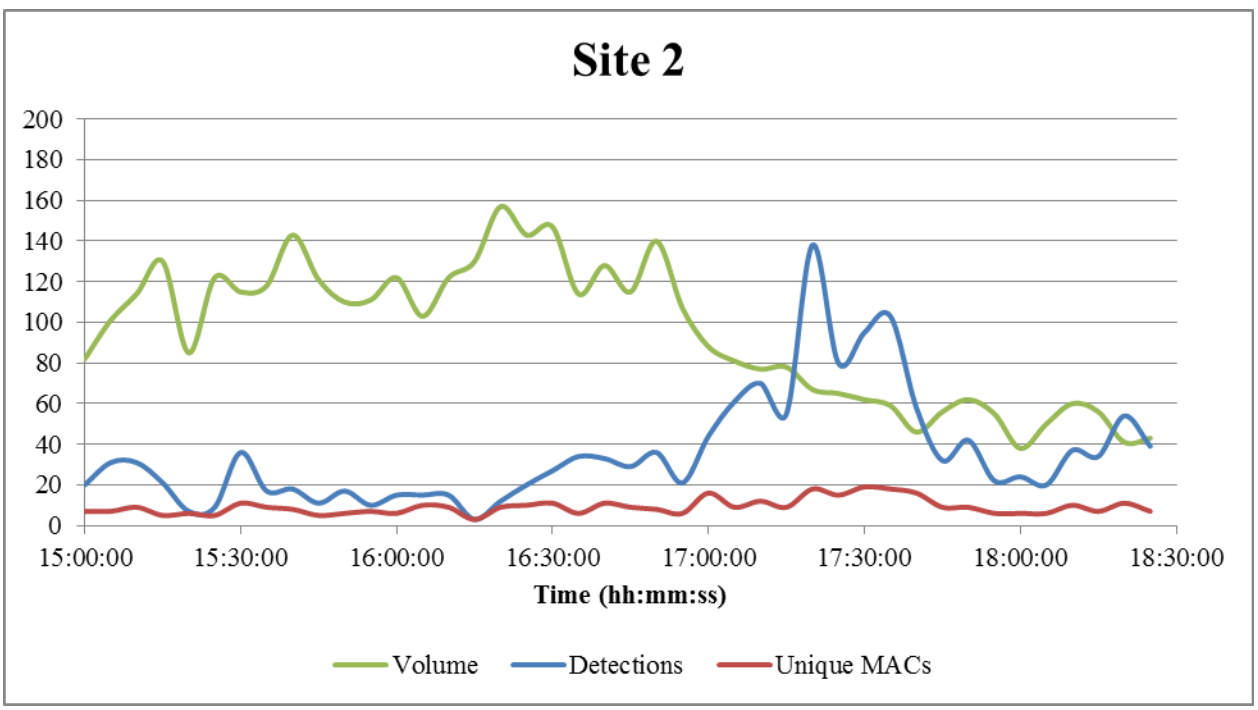


Figure 12. Traffic Volumes, Detections, and Unique MAC Addresses for Site 2

As was previously mentioned, Site 1 experienced free-flow conditions for most of the study period and thus, maintained a higher level of vehicle throughput than Site 2. The peaks in detections may potentially be the result of the queue from the intersection at 14th Street occasionally extending back into the detection zone of Site 1, although further analysis is necessary to confirm this hypothesis. Site 2's traffic volumes were much different than Site 1's. The vehicle queue spillback from downstream intersections resulted in significant congestion at Site 2 starting at approximately 4:30 PM. Consequently, vehicles dwelled in the detection zone of Site 2 for extended periods of time, increasing not only the likelihood of unique MAC address detection, but also the number of times each MAC address was reported. These occurrences were observed in the video data.

The following graphs, Figure 13 and Figure 14 display the detection rates for each site. These rates were calculated by dividing the number of unique MAC addresses detected by the traffic volumes at each site. As was previously mentioned, Site 2 obtained higher detection rates than Site 1 which may be due to the heavy congestion experienced at Site 2, resulting in a greater likelihood that a discoverable Bluetooth device would be detected.

The detection rates for Site 2 before 5:00 PM are similar to those of Site 1, but while Site 1's detection rates were close to 5 percent for the entire study period, Site 2's detection rates peaked at 5:40 PM. A peak detection rate of 35 percent significantly exceeds rates which have been found in other studies and is unexpected. Initial investigations have not been able to determine if this result is correct or is due to an unknown error in the analysis procedure compounded by the congested conditions. Future research efforts will seek to clarify these unexpected values.

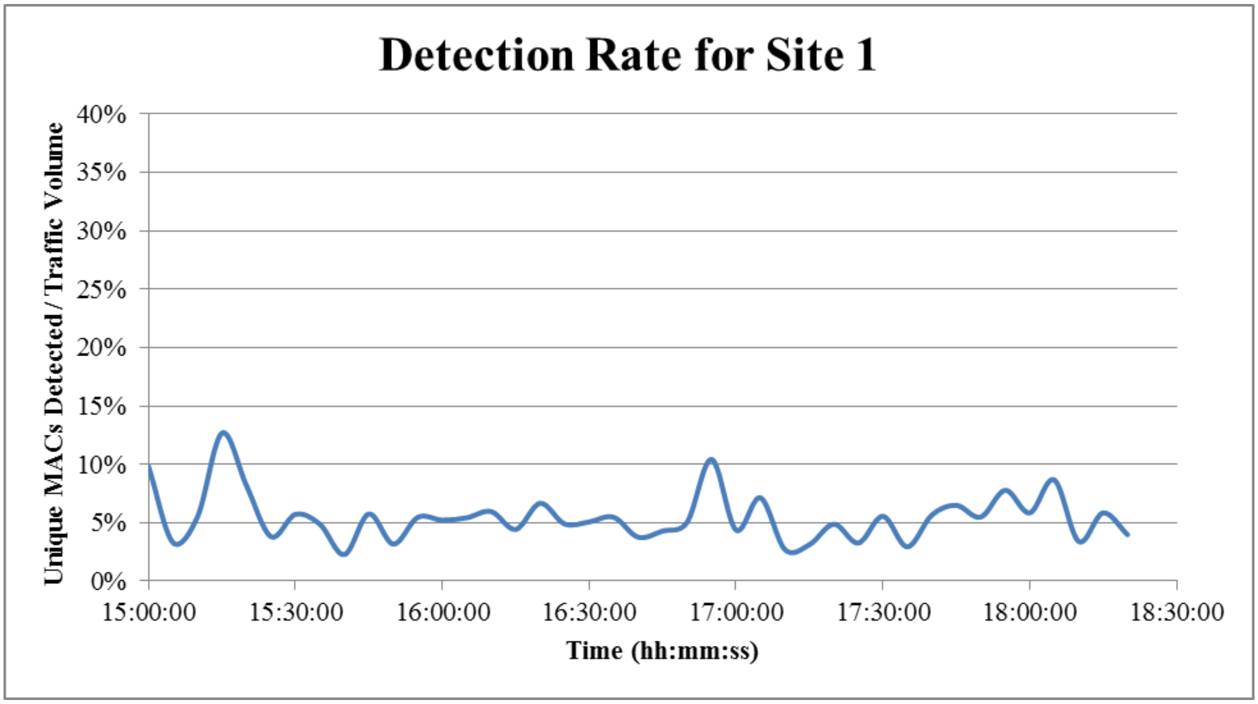


Figure 13. Five-Minute Detection Rates for Site 1

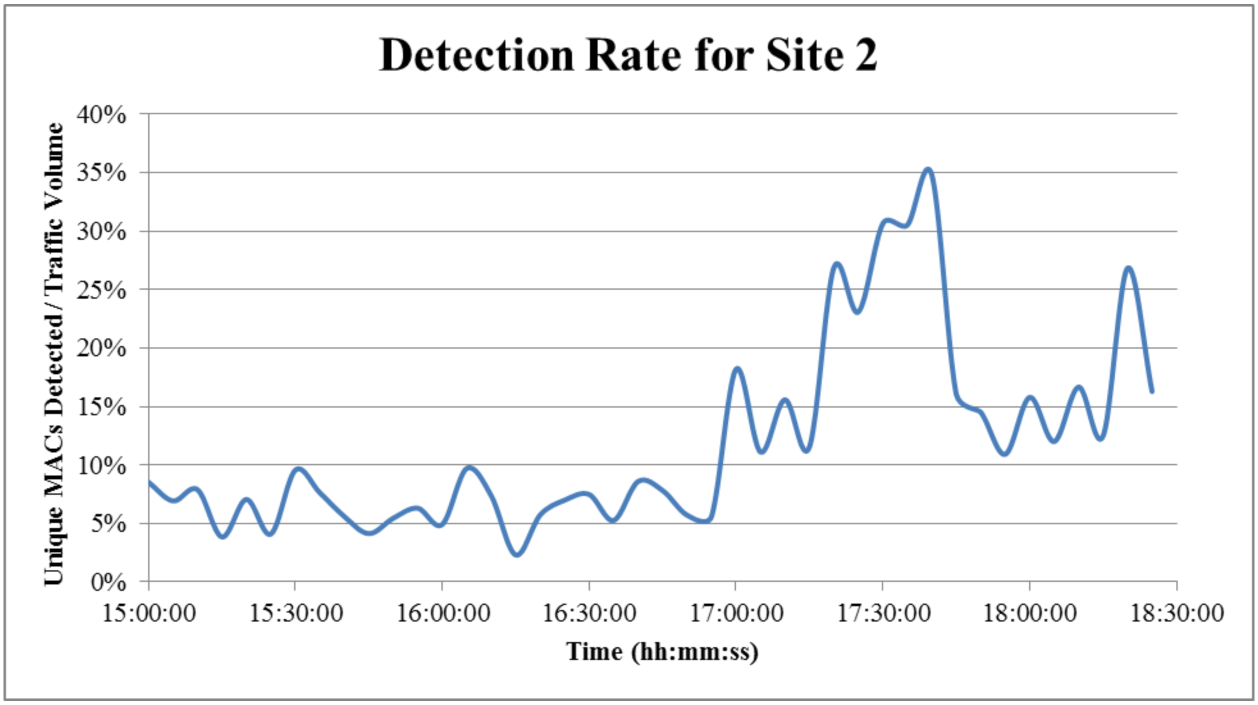


Figure 14. Five-Minute Detection Rates for Site 2

5.1.1.5 Probe Vehicle Devices

Probe vehicle 1, which consistently traveled in the inside lane (closest to the Bluetooth stations), completed 14 passes through the study segment, while probe vehicle 2 completed 20 passes driving in the outside lane (farthest from the Bluetooth stations). The percentages of passes detected by each Bluetooth reader for each probe vehicle were calculated and are compared in this section. Table 7 presents the percentage of passes that were detected for the Class 1 probe devices (the Bluetooth USB adapters placed on the passenger-side seats and floors). Table 8 shows the percentage of passes detected for the Class 2 probe devices (the Bluetooth-enabled GPS loggers placed on the dashboards). The tables are color coded where the values closest to zero percent are red and the values closest to one hundred percent are green.

Table 7. Percentage of Detected Passes for Class 1 Probe Devices by Bluetooth Reader

Travel Lane	Class 1 Probe Device	Detection Rate by Reader Height:								Average
		Site 1				Site 2				
		7'	10'	10'	14.5'	7'	10'	10'	14.5'	
Inside (closest to Bluetooth station)	1	71%	57%	71%	64%	64%	64%	57%	71%	65%
	3	86%	50%	64%	79%	50%	64%	50%	79%	65%
	5	36%	29%	21%	57%	71%	50%	36%	43%	43%
Outside (farthest from Bluetooth station)	2	60%	35%	35%	30%	65%	45%	40%	60%	46%
	4	45%	40%	45%	45%	65%	30%	35%	65%	46%

Table 8. Percentage of Detected Passes for Class 2 Probe Devices by Bluetooth Reader

Travel Lane	Class 2 Probe Device	Detection Rate by Reader Height:								Average
		Site 1				Site 2				
		7'	10'	10'	14.5'	7'	10'	10'	14.5'	
Inside (closest to Bluetooth station)	7	29%	21%	36%	43%	29%	21%	29%	21%	29%
	9	64%	36%	36%	71%	50%	43%	36%	57%	49%
Outside (farthest from Bluetooth station)	6	5%	5%	30%	5%	35%	35%	20%	65%	25%
	8	15%	15%	30%	20%	45%	20%	15%	65%	28%

The Class 1 Bluetooth devices placed in the probe vehicle traveling in the inside lane were more frequently detected than the Class 1 Bluetooth devices in the probe vehicle traveling in the outside lane. Although the Bluetooth readers have ideal detection ranges of 330 feet, proximity affects the strength of the Bluetooth signal, as evident by the results in Table 8. The same relationship may be observed for the Class 2 Bluetooth devices. For both sets of Bluetooth devices, the Site 2 Bluetooth readers yielded greater detection rates as a result of the heavy congestion as described in previous sections. Finally, the Class 1 devices were detected a greater number of times than the Class 2 devices, which is a result of the difference in transmitting powers and connectivity ranges. Class 2 devices are less powerful and are only required to transmit over 33 feet compared to 330 feet for Class 1 devices.

5.2 System Performance Metrics

System performance metrics for this study require datasets from two Bluetooth stations. One such performance metric is travel time accuracy, i.e. the accuracy of the travel times produced by the Bluetooth stations compared to the ground truth travel times measured by the GPS data loggers. To calculate the travel times, the time-stamps of matched MAC addresses are compared. The match rate, which is the number of matched MAC addresses out of the total traffic volume, is then understood to be a key performance metric. A sufficient number of matched MAC addresses yields calculated travel times that will more accurately represent actual travel times for the roadway.

5.2.1 Match Rates

The match rate is defined as the number of unique MAC addresses detected at both Site 1 and Site 2 divided by the number of vehicles that traveled the study segment. The number of unique MACs detected at Site 1 but not at Site 2 and vice versa are discussed in Section 5.2.2. The number of matched MAC addresses determines the sample size of travel times that may be calculated and influences the accuracy of reported travel times. The number of MAC addresses detected at Site 1 exclusively, Site 2 exclusively, or both are presented in Table 9 and Figure 15.

Table 9. Unique MAC Addresses Detected between Site 1 and Site 2

Inter-site Pairs	Site 1	Both	Site 2	Total
All	181	71	257	509
7'	83	25	178	286
10'	134	28	131	293
14.5'	89	18	188	295

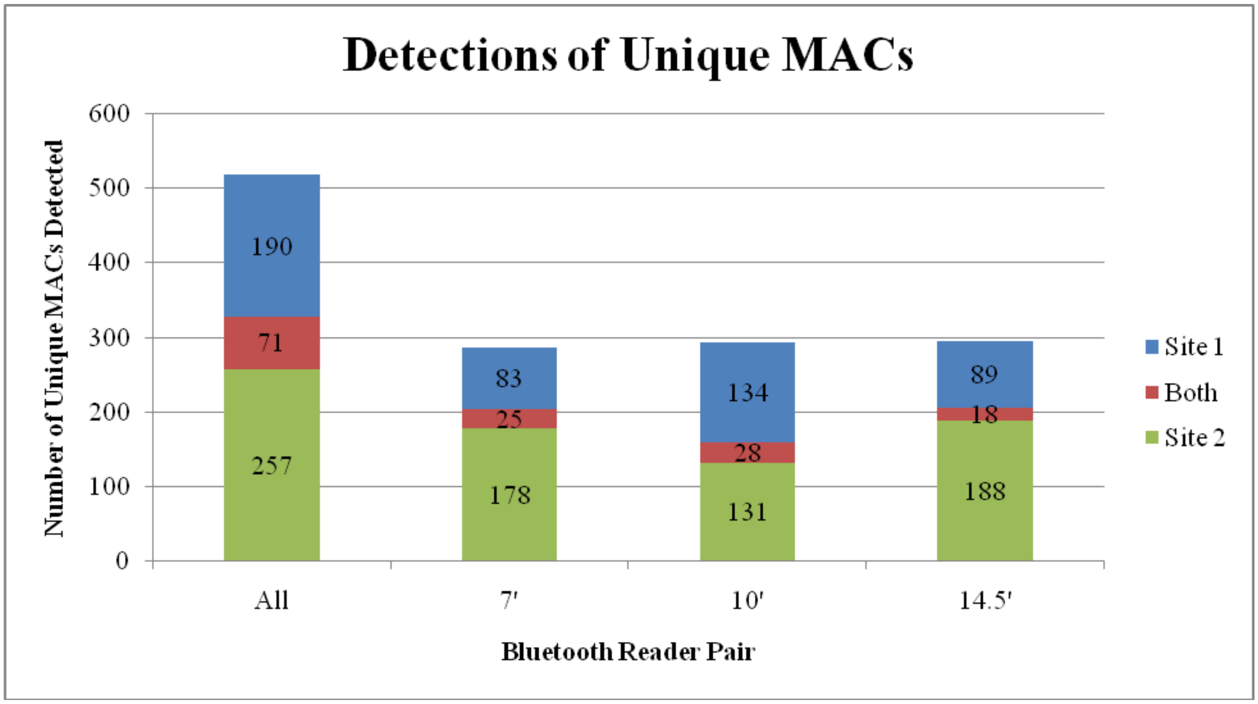


Figure 15. Unique MAC Addresses Detected at Sites 1 and 2 by Reader Height

The reader placed at 7 feet at Site 2 malfunctioned in the field and reported erroneous time-stamps for detections that could not be used. Therefore, the data produced by that reader are not considered in the following calculation of the overall match rate. Without the Bluetooth reader placed at 7 feet at Site 2, 56 unique MAC addresses were matched between both sites.

An estimation of the number of vehicles traveling the entire study segment is necessary to calculate an accurate match rate. Calculating match rates is easier for freeway studies, because a study segment can be defined to exclude on-ramps and off-ramps, and the number of vehicles traveling the entire segment may be determined. This is not the case with the Spring Street study segment. During the study period, the number of vehicles that traveled past Site 1 was greater than the number that traveled past Site 2 (5,876 vehicles at Site 1 versus. 3,964 vehicles at Site 2). No means of determining the number of vehicles that drove past both sites was utilized, but will be considered in future research. It is difficult to estimate this number in this case study, because it is likely that vehicles both entered and exited the study segment via cross-streets. In an effort to produce a number to calculate the match rate, the traffic volume at Site 2 was used because it is impossible that any more than 3,964 vehicles from Site 1 passed through Site 2's detection zone.

Consequently, the total traffic volume that traveled past Site 2 (3,964 vehicles) will be used as a conservative estimate of the number of vehicles that passed both sites, understanding that it is very unlikely that all of the vehicles that passed Site 2 also traveled past Site 1. The match rate is then calculated by dividing 56 by 3,964 which equals 1.4 percent. A match rate of 1.4 percent is a conservative estimate for this field study.

5.2.2 Loss Rates

The data loss rate is calculated to better understand Bluetooth travel time monitoring. Out of the 261 MAC addresses detected at Site 1, only 71 (27.2 percent) were also detected at Site 2. Out of 328 MAC addresses detected at Site 1, only 71 (21.6 percent) were detected at Site 1. The data loss is substantial, where 72.8 percent of the MAC addresses detected at Site 1 are not detected at Site 2. One source of data loss may be attributed to vehicles departing the study segment before reaching Site 2. The high data loss rate may also be attributed to Bluetooth devices being detected at Site 1 and traveling through Site 2's detection zone without being detected.

5.2.3 Travel Times and Travel Time Accuracy

Travel times for the study corridor were produced using three different datasets: the GPS logger data, the Bluetooth data of the Bluetooth devices in the probe vehicles, and the Bluetooth data of matched MAC addresses. The GPS logger travel times serve as the ground truth data to which the other two sets of travel times are compared. Outlying data points are also discussed in this section.

5.2.3.1 GPS versus Probe Vehicle Bluetooth Devices

Nine Bluetooth-enabled devices were placed inside the two probe vehicles. GPS travel times were produced by calculating the difference in the times at which the GPS logger coordinates most closely matched the latitudinal and longitudinal coordinates of both sites. The Bluetooth travel times were measured by determining the difference in time-stamps of the first detection of a unique MAC address at each site. The descriptions of the devices are listed in Table 10. Following this table is Figure 16, which shows both the GPS logger travel times and Bluetooth travel times for probe vehicle 1. Table 11 presents the travel times by device and the calculated error. Table 12 presents the error for the travel times calculated for each Bluetooth device in probe vehicle 1.

Table 10. Descriptions of Probe Vehicle Bluetooth Devices

Device Number	Device Type	Antenna Class	Probe Vehicle	Travel Lane	In-Vehicle Location
1	Sabrent Class 1 BT-USB Adapter	1	1	inside	floor
2	Sabrent Class 1 BT-USB Adapter	1	2	outside	floor
3	Sabrent Class 1 BT-USB Adapter	1	1	inside	seat
4	Sabrent Class 1 BT-USB Adapter	1	2	outside	seat
5	Sabrent Class 1 BT-USB Adapter	1	1	inside	seat
6	BT Logger GPS BT-335	2	2	outside	dash
7	BT Logger GPS BT-335	2	1	inside	dash
8	Qstarz Travel Recorder XT	2	2	outside	dash
9	Qstarz Travel Recorder XT	2	1	inside	dash

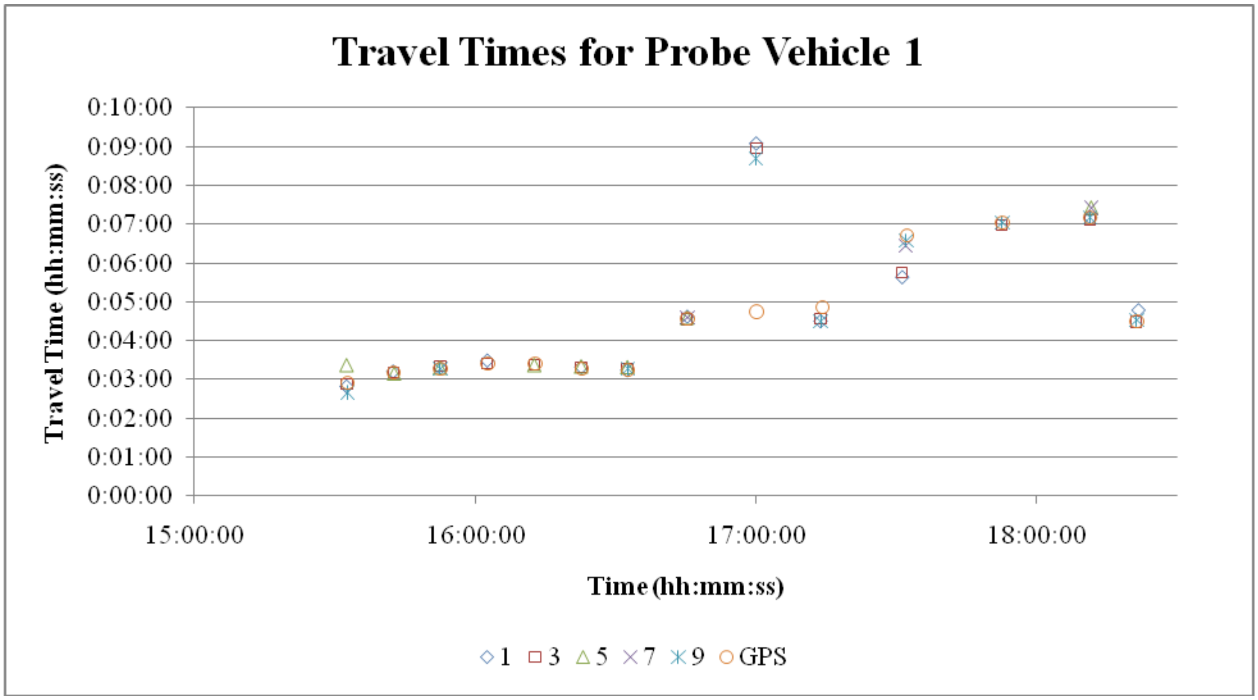


Figure 16. Travel Time Comparison of GPS and Bluetooth Devices for Probe Vehicle 1

Table 11. GPS and Bluetooth Travel Times for Probe Vehicle 1

Run	GPS TT	Bluetooth Device TT					Bluetooth Average	Bluetooth Standard Deviation	Expected Error
		1	3	5	7	9			
1	2:55	2:49	2:53	3:22		2:40	2:56	0:18	0.6%
2	3:11	3:12	3:11	3:09			3:11	0:02	0.2%
3	3:17	3:18	3:20	3:18		3:17	3:18	0:01	0.6%
4	3:25	3:29	3:25				3:27	0:03	1.0%
5	3:24		3:22	3:22			3:22	0:00	1.0%
6	3:17	3:19	3:18	3:20			3:19	0:01	1.0%
7	3:14	3:14	3:16	3:19		3:16	3:16	0:02	1.2%
8	4:34	4:37	4:33	4:35	4:36		4:35	0:02	0.5%
9	4:45	9:05	8:57			8:42	8:55	0:12	87.6%
10	4:52	4:30	4:34			4:30	4:31	0:02	7.1%
11	6:43	5:38	5:45		6:27	6:35	6:06	0:29	9.1%
12	7:02		6:59			7:03	7:01	0:03	0.2%
13	7:10	7:10	7:07	7:25	7:25	7:11	7:16	0:09	1.3%
14	4:30	4:47	4:29			4:32	4:36	0:10	2.2%

Table 12. Error in Bluetooth Travel Times for Probe Vehicle 1

Run	Error by Bluetooth Device TT					
	1	3	5	7	9	Average Error
1	3.4%	1.1%	15.4%		8.6%	7.1%
2	0.5%	0.0%	1.0%			0.5%
3	0.5%	1.5%	0.5%		0.0%	0.6%
4	2.0%	0.0%				1.0%
5		1.0%	1.0%			1.0%
6	1.0%	0.5%	1.5%			1.0%
7	0.0%	1.0%	2.6%		1.0%	1.2%
8	1.1%	0.4%	0.4%	0.7%		0.6%
9	91.2%	88.4%			83.2%	87.6%
10	7.5%	6.2%			7.5%	7.1%
11	16.1%	14.4%		4.0%	2.0%	9.1%
12		0.7%			0.2%	0.5%
13	0.0%	0.7%	3.5%	3.5%	0.2%	1.6%
14	6.3%	0.4%			0.7%	2.5%

Except for probe vehicle 1 runs 1, 9, 10, and 11, the average errors between the GPS travel times and average Bluetooth device travel times were less than 2 percent. There is an 87.6 percent error for run 9 because it was during this run that probe vehicle 1 stopped to exchange drivers, taking almost twice as long to travel the study segment. This driver exchange took place within Site 1's detection zone and the timestamp of its first detection was used to calculate its travel time. Probe vehicle 1 completed runs 10 and 11 at 5:13 PM and 5:31 PM respectively, when Site 2 experienced the highest levels of congestion. It is not clear why large errors exist for run 11, but may be attributed to how the data was processed. Future research will seek to better understand the error.

The Bluetooth travel times for these runs are shorter than the GPS travel times most likely because the Bluetooth devices were detected before the probe vehicle passed the Bluetooth station. These data show that the Bluetooth station configuration and analysis procedure used for this study accurately report travel times during free-flow conditions, but perform poorly when calculating travel times for vehicles on roadways segments experiencing heavy congestion. Future research will investigate if the analysis may be improved to produce accurate travel times during heavy congestion, by means such as using last detections to calculate travel times, picking latitudinal and longitudinal coordinates upstream to match the edge of the Bluetooth station's detection zone, etc.

The same analysis is conducted for probe vehicle 2. Figure 17 shows the GPS logger travel times plotted with the Bluetooth travel times for probe vehicle 2. Table 13 presents the numerical data. Table 14 presents the error for the travel times calculated for each Bluetooth device in probe vehicle 2.

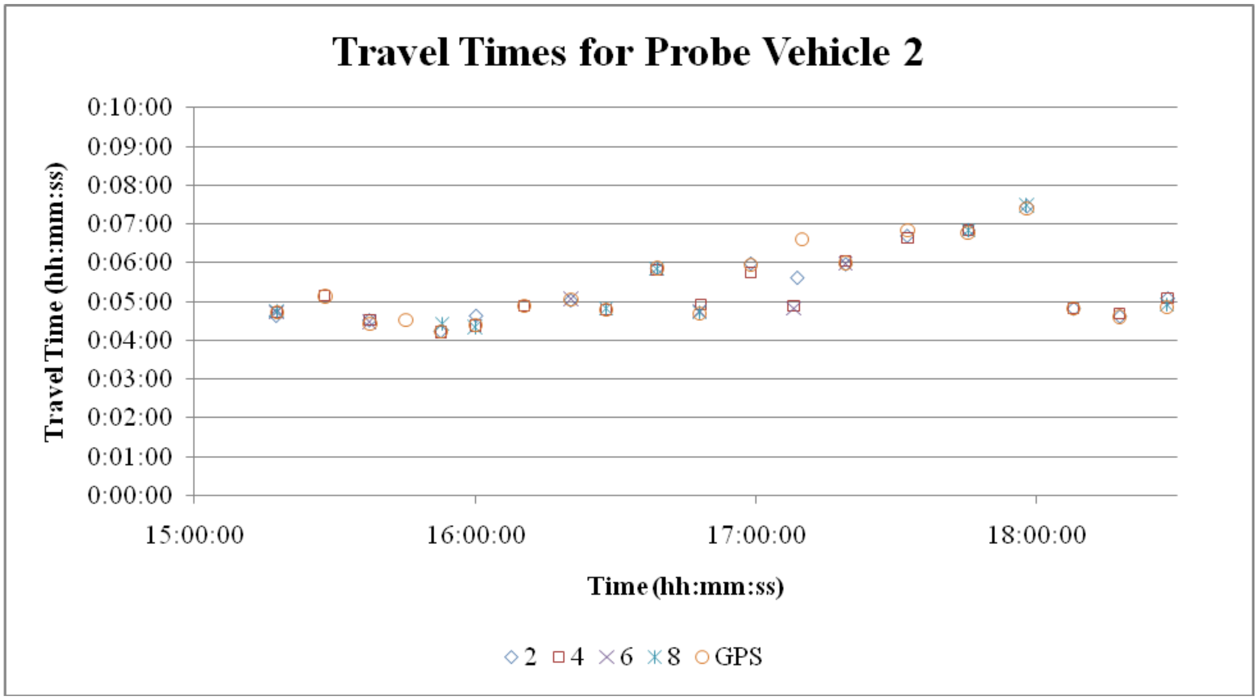


Figure 17. Travel Time Comparison of GPS and Bluetooth Devices for Probe Vehicle 2

Table 13. GPS and Bluetooth Travel Times for Probe Vehicle 2

Run	GPS TTs	Bluetooth Device TTs				Bluetooth Average	Bluetooth Standard Deviation	Expected Error
		2	4	6	8			
1	4:43	4:38	4:44	4:43	4:45	4:43	0:03	0.2%
2	5:08		5:09			5:09	n/a	0.3%
3	4:26	4:31	4:31	4:29		4:30	0:01	1.6%
4	4:32					n/a	n/a	n/a
5	4:14	4:14	4:13		4:26	4:18	0:07	1.4%
6	4:24	4:38	4:23		4:21	4:27	0:09	1.3%
7	4:54		4:54			4:54	n/a	0.0%
8	5:03	5:02		5:04		5:03	0:01	0.0%
9	4:48		4:48		4:49	4:48	0:01	0.2%
10	5:52	5:52	5:49		5:51	5:51	0:02	0.4%
11	4:42		4:56	4:45	4:43	4:48	0:07	2.1%
12	5:57	5:59	5:45			5:52	0:10	1.4%
13	6:37	5:37	4:53	4:50		5:07	0:26	22.8%
14	6:00	5:58	6:03	5:59		6:00	0:03	0.0%
15	6:50	6:42	6:39			6:41	0:02	2.3%
16	6:47	6:51	6:51		6:50	6:51	0:01	0.9%
17	7:24	7:28			7:29	7:28	0:01	1.0%
18	4:49	4:49	4:50			4:50	0:01	0.2%
19	4:37	4:37	4:42			4:39	0:04	0.9%
20	4:51	5:05	5:05		4:55	5:02	0:06	3.7%

Table 14. Error in Bluetooth Travel Times for Probe Vehicle 2

Run	Error by Bluetooth Device TT				
	2	4	6	8	Average Error
1	1.8%	0.4%	0.0%	0.7%	0.7%
2		0.3%			0.3%
3	1.9%	1.9%	1.1%		1.6%
4					
5	0.0%	0.4%		4.7%	1.7%
6	5.3%	0.4%		1.1%	2.3%
7		0.0%			0.0%
8	0.3%		0.3%		0.3%
9		0.0%		0.3%	0.2%
10	0.0%	0.9%		0.3%	0.4%
11		5.0%	1.1%	0.4%	2.1%
12	0.6%	3.4%			2.0%
13	15.1%	26.2%	27.0%		22.8%
14	0.6%	0.8%	0.3%		0.6%
15	2.0%	2.7%			2.3%
16	1.0%	1.0%		0.7%	0.9%
17	0.9%			1.1%	1.0%
18	0.0%	0.3%			0.2%
19	0.0%	1.8%			0.9%
20	4.8%	4.8%		1.4%	3.7%

Probe vehicle 2’s driver exchange (run 13) was executed within Site 2’s detection zone, but upstream of the Bluetooth station. This resulted in a Bluetooth travel time that was approximately 23 percent shorter than the GPS travel time. The average percent errors for probe vehicle 2 were less than 4 percent without run 13. Probe vehicle 2’s travel times were not influenced in the same way as probe vehicle 1’s travel times. Runs 14 and 15 were completed at 5:19 PM and 5:32 PM respectively, but the Bluetooth travel times are not substantially shorter than the GPS travel times. This may be due to the right lane holding shorter queues as a result of vehicles turning right onto 4th Street to find an alternate route.

5.2.3.2 Non-Probe Vehicle Bluetooth Devices

Travel times were produced for each unique MAC address that was detected at both Site 1 and Site 2 for all readers. The difference in time-stamps of the MAC addresses' initial detections are the travel times of the vehicles in which the Bluetooth devices were being carried. Figure 18 shows the calculated Bluetooth travel times, excluding the probe vehicle Bluetooth devices. Two major outliers are not shown in Figure 18. A travel time of two hours, nine minutes, and twenty-three seconds was calculated at 5:09 PM. Another travel time of two hours, eighteen minutes, and fifty-eighty seconds was measured for a Bluetooth device which traveled into Site 2's detection zone at 5:31 PM. These outliers will be further discussed in Section 5.2.3.3.

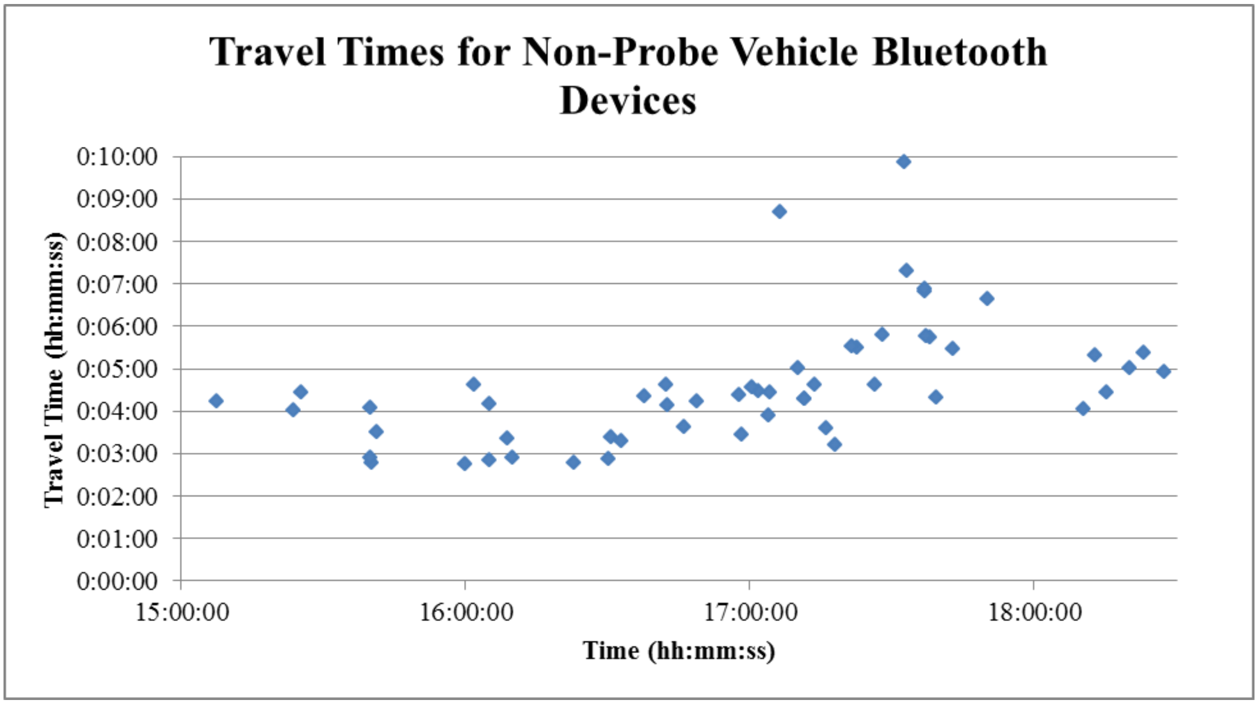


Figure 18. Travel Times Produced from Matched MAC Addresses

Groups of travel time points may be observed in Figure 18, which may indicate platoons, possibly formed when vehicles departed the upstream intersection. Two travel times calculated at 5:06 PM and 5:32 PM are substantially longer than the rest of the travel times, suggesting that the owners of these Bluetooth devices may have diverted from Spring Street prior to passing Site 2. These outliers will be further discussed in Section 5.2.3.3.

A gap in the travel time data may be observed at 6:00 PM. It is not known whether this gap is a representative finding or if it occurred due to an error in the equipment or analysis. Future efforts will seek to clarify this issue.

5.2.3.3 Outlying Data Points

The outlying travel time data are presented in Table 15. Several fast food restaurants and gas stations exist along Spring Street within the study section. This may explain the travel times measuring 8 to 10 minutes. The travel times greater than 2 hours are likely a result of drivers diverting from Spring Street for an extended period of time. These vehicles may have traveled past Site 1, stopped and parked or continued on to a destination not on Spring Street, and returned to Spring Street passing by Site 2. However, it is important to note that it is not possible to determine the exact reason for these travel times. The nature of Bluetooth data only allow for a sample of vehicle trips at limited points along their trip (which in this case is two points). Data collection is essentially blind to all other parts of the trip.

Table 15. Bluetooth Travel Time Outliers

Time	Travel Time (hh:mm:ss)
17:06:20	0:08:42
17:09:42	2:09:23
17:31:27	2:18:58
17:32:40	0:09:52

For real-time reporting of Bluetooth travel times, filters must dynamically remove outliers to prevent inaccurate travel time reports. For study corridors that do not experience high variability in travel times, an upper bound and a lower bound for travel times may be defined, where any travel times that fall outside of that range are considered outliers. For Spring Street, an arterial which experienced high variability during this field test, a filter may be developed which considers a travel time invalid if it is a certain percentage shorter or longer than the average of a number of previous travel times. However, such a filter must be developed and tested with extreme caution as such a filter could readily eliminate critical data indicating incident-based congestion or other non-typical behavior that is occurring.

5.2.3.4 Travel Time Comparison

The travel times produced via matched MAC addresses are now compared to the GPS data logger travel times. Figure 19 presents both travel time data sets and travel time averages are shown in Table 16.

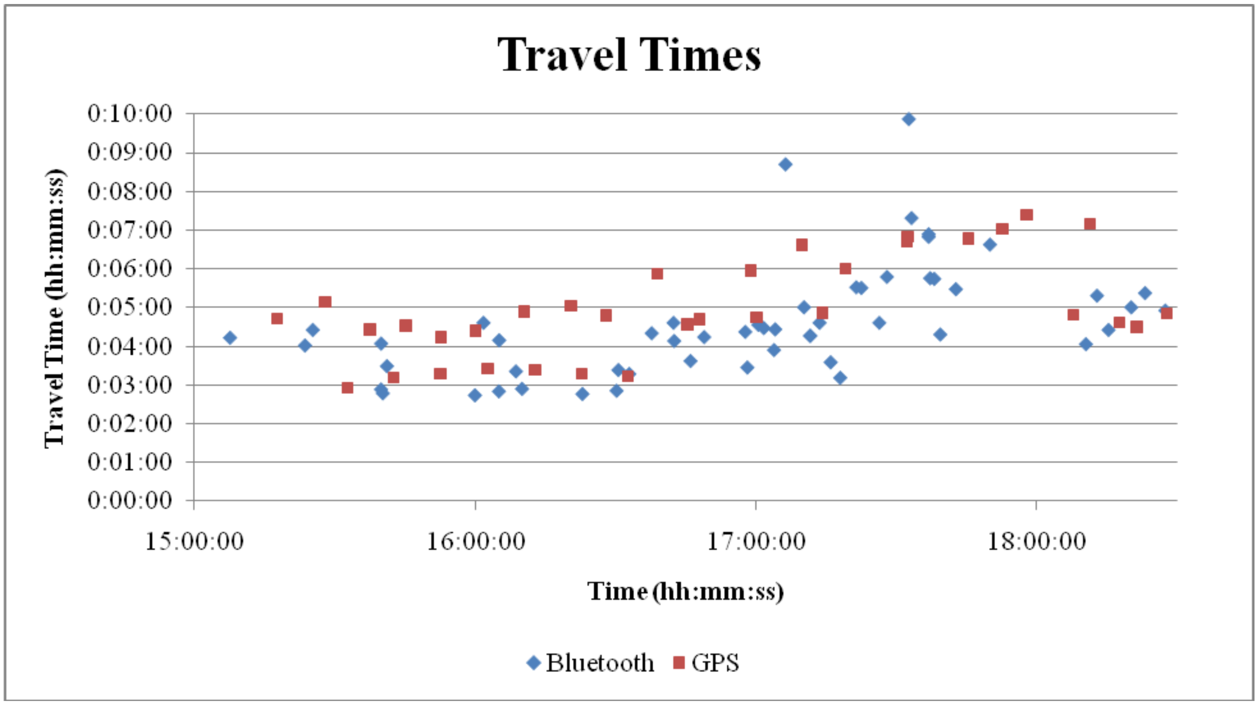


Figure 19. Bluetooth and GPS Travel Times for Study Period

Table 16. Bluetooth and GPS Travel Times

Source of Travel Time Data	Average Travel Time	Standard Deviation	Sample Size
Bluetooth	9:14	24:19	56
Bluetooth (without Outliers)	4:25	1:07	52
GPS Data Loggers	4:58	1:16	34

The Bluetooth travel times appear to be shorter than the GPS travel times. This may be attributed to the probe vehicles traveling only within the inside and outside lanes, resulting in the operators having to slow down for vehicles which were parking, turning right or left onto cross-streets, or traveling slowly to avoid collisions with parked vehicles. It is also possible that a general bias may exist between the methods of travel time analysis, i.e. Bluetooth using the first data point read and GPS based on the location of the readers. However, additional study is needed and reasons for such an effect will be monitored in future experiments.

5.3 Summary

Two different sets of performance metrics were analyzed in this chapter. The data and performance metrics at each site were described, starting with a discussion of the difference in traffic volumes at each site. The overlaps of MAC addresses detected at each site were also discussed and suggest that multiple readers may produce greater detection rates than a single reader. An explanation was also provided concerning the decision to treat the two Bluetooth readers placed at 10 feet as a single reader. Further research will determine the effects of interference between two readers placed directly adjacent to one another.

From the MAC address data and volume data, detection rates were calculated for each Bluetooth reader over the study period, for each site over the study period, and for each site over five-minute intervals. The detection rates at Site 2 were significantly higher than those at Site 1, which may be due to vehicles dwelling within Site 2's detection zone for extended periods, increasing the likelihood that any discoverable devices in those vehicles would be detected.

Finally, the detections of the probe vehicles were examined. As expected, the Class 1 Bluetooth devices were detected more frequently than the Class 2 devices. Furthermore, the Bluetooth devices in probe vehicle 1, which traveled in the lane closest to the Bluetooth stations, were detected more frequently than the devices in probe vehicle 2.

The performance metrics for the Bluetooth system were than assessed and included match rates, data loss rates, and travel time accuracy. Outlying data points were also discussed.

This research found that the Bluetooth travel times matched the ground truth travel times produced by the GPS data loggers inside the probe vehicles.

CHAPTER 6: CONCLUSION

This study was motivated by the desire to develop a methodology for measuring travel times on arterial roads using Bluetooth, to better understand Bluetooth technology and its implications for an optimal configuration of a Bluetooth station, and to assess the accuracy of Bluetooth travel time measurements. The methodology utilized for the case study on Spring Street is described and its results and data analysis are presented. The Bluetooth system was able to report travel times which matched ground truth travel times, as determined by GPS-equipped probe vehicles, with a high level of accuracy. A conservative estimate for the match rate for this study is 1.4 percent. However, the true match rate is likely higher. The interference between two Bluetooth readers placed in the same position was investigated, but requires a more in-depth evaluation. As expected, Bluetooth devices in the probe vehicle traveling the lane closest to the Bluetooth stations were detected more frequently than the Bluetooth devices in the probe vehicle traveling in the farthest lane.

6.1 Recommendations

The methodology presented in this study may be improved in several ways for future implementations of Bluetooth travel time studies. The match rate is a function of the number of vehicles that traveled the entire study segment. Therefore, counts for traffic which traverses the entire study corridor must be conducted in addition to site-specific traffic counts. One way in which to determine the traffic volumes traversing the entire study segment is to utilize automatic license plate readers. With license plate data an accurate match rate may be determined.

The data output of the Bluetooth readers should be modified to include the device name, which is either manufacturer-defined or owner-defined. The logging of device names would assist in determining the type of device detected. In addition, the received signal strength index (RRSI) may be included in the data output which may be able to provide travel lane information. As the distance between two Bluetooth devices increases, the RSSI decreases. Further studies are required to gain a better understanding of this relationship.

A method of automatically transferring MAC address data and reporting travel times in real-time is a critical next step for this Bluetooth system. Optimizing the Bluetooth units for easier portable deployment would allow for studies spanning longer periods of time. Bluetooth stations may be outfitted with modems which would transmit Bluetooth data back to a central processing unit.

6.2 Future Research

There are a number of opportunities for further research in the field of Bluetooth travel time monitoring. The GPS logger data (collected by Bluetooth-enabled GPS logger devices) may be integrated with the Bluetooth detection data to estimate the detection zones of Bluetooth readers and visually represented in a geographic information system.

An in-depth investigation is required to determine the effects of placing two Bluetooth readers in the same location. A field test may be implemented in which one site is outfitted with one Bluetooth reader while the next site is equipped with two Bluetooth readers positioned in the same place. One can decrease biases in the comparison of data by placing the Bluetooth stations close enough to reduce the number of vehicles entering or exiting the study corridor from cross-streets.

An experiment placing Bluetooth readers at varying heights along with varying offsets would further clarify the influence of placement on detection rate and provide greater understanding of an optimal configuration for different classifications of roadways. Several different configurations of Bluetooth stations may be deployed in the experiment, where each station would be characterized by different offsets from the roads and different vertical placement of Bluetooth readers.

Finally, a major improvement to the Bluetooth system utilized in this study would be the study and development of an algorithm to automatically calculate travel times from the Bluetooth data collected from vehicles in real-time. Potential improvements in the calculated travel time should also be explored for inclusion in the system, such as last-to-last detections, as well as filters which would omit outlying travel times.

APPENDIX A

INSTRUCTIONS FOR USING THE NETBOOKS, BLUETOOTH ADAPTERS, UBUNTU & PERL SCRIPTS TO COLLECT MAC ADDRESSES

1. Insert any Bluetooth adapter into the USB port **closest to you on the right side** of any netbook.
2. Press the power button to power on or return the netbook from sleep mode.
3. Ensure the netbook's wireless adapter is on and the netbook is connected to the Internet by cycling through the netbook adapter options via "Fn"+"F2". "WLAN ON & Bluetooth OFF" should be displayed as in figure 1. The netbook should be connected to GTwpa as displayed in figure 2.

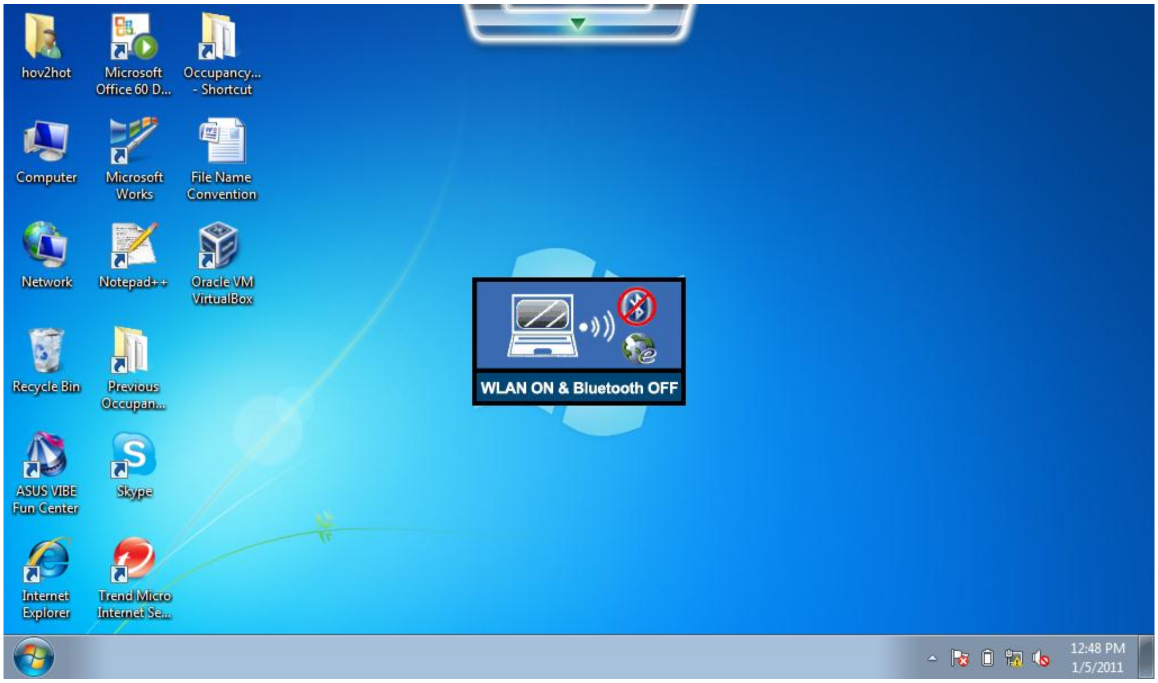


Figure 1. Enabling the netbook's wireless adapter.

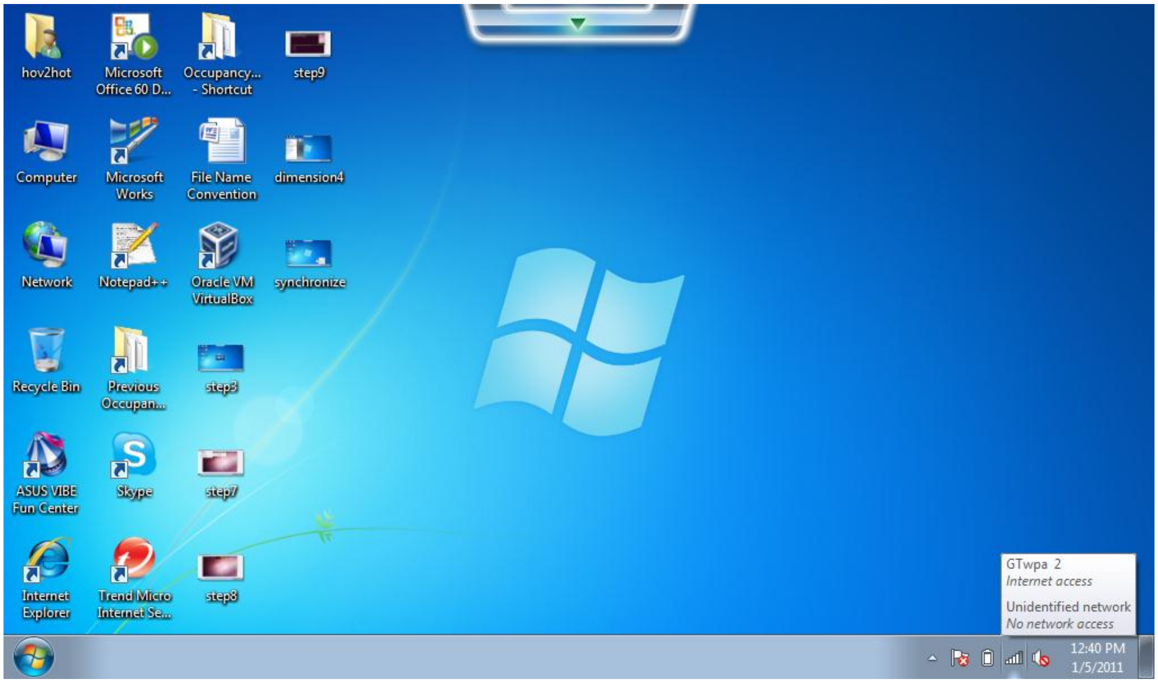


Figure 2. Ensuring the netbook is connected to the GTwpa network.

4. Select "Dimension 4 v5.0" from the program list as shown in figure 3. If a User Account Control window appears, select "Yes."

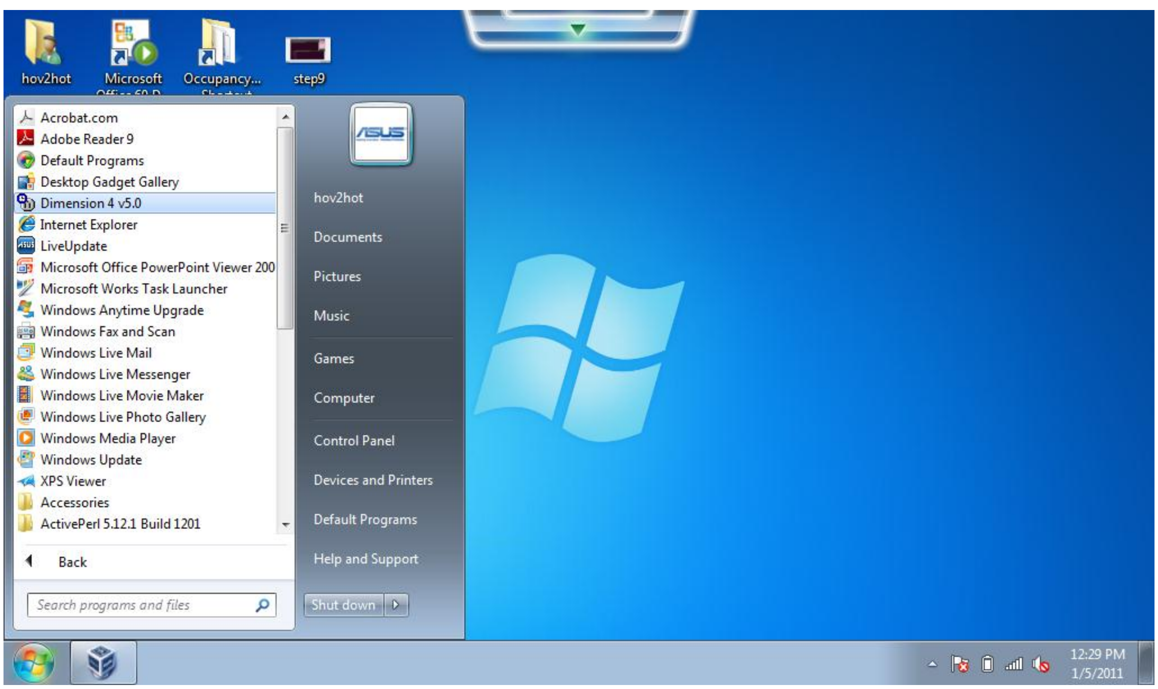


Figure 3. Opening Dimension 4 v5.0 from the Program List.

5. Right-click the Dimension 4 icon in the Taskbar and select “Synchronize Now” as shown in figure 4.

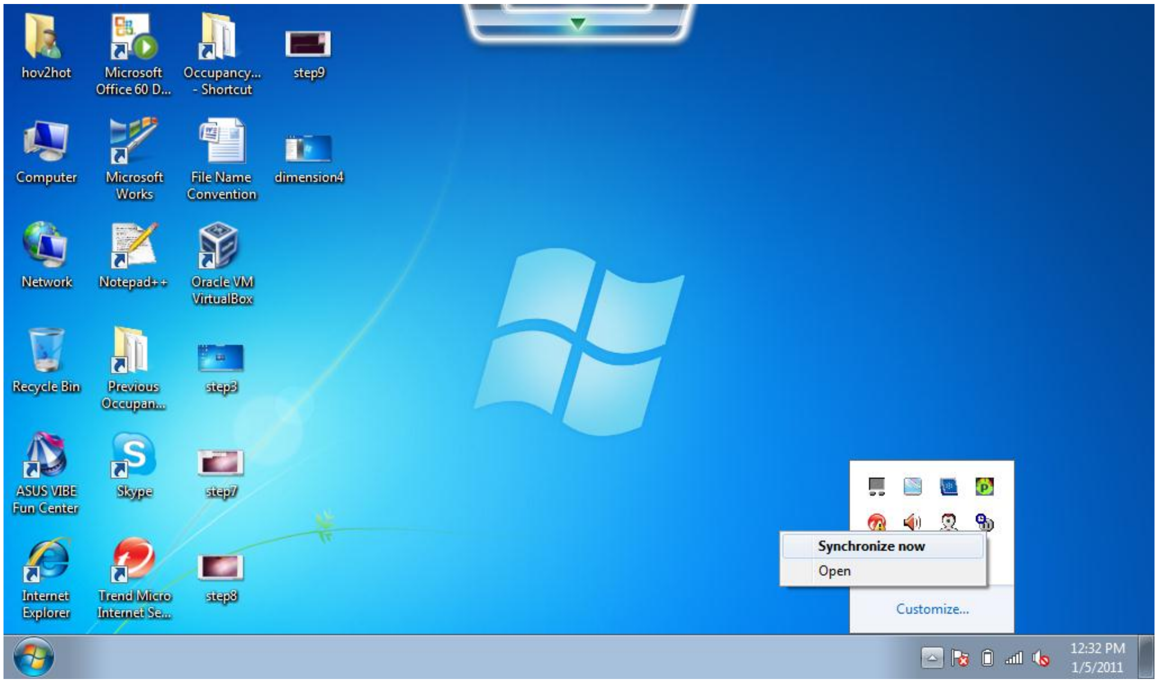


Figure 4. Selecting "Synchronize now" from Dimension 4 v5.0 in Taskbar.

6. Turn off the netbook’s wireless and Bluetooth adapters by cycling through the netbook adapter options via “Fn”+”F2” to conserve battery power. “WLAN & Bluetooth OFF” should be displayed as in figure 5.

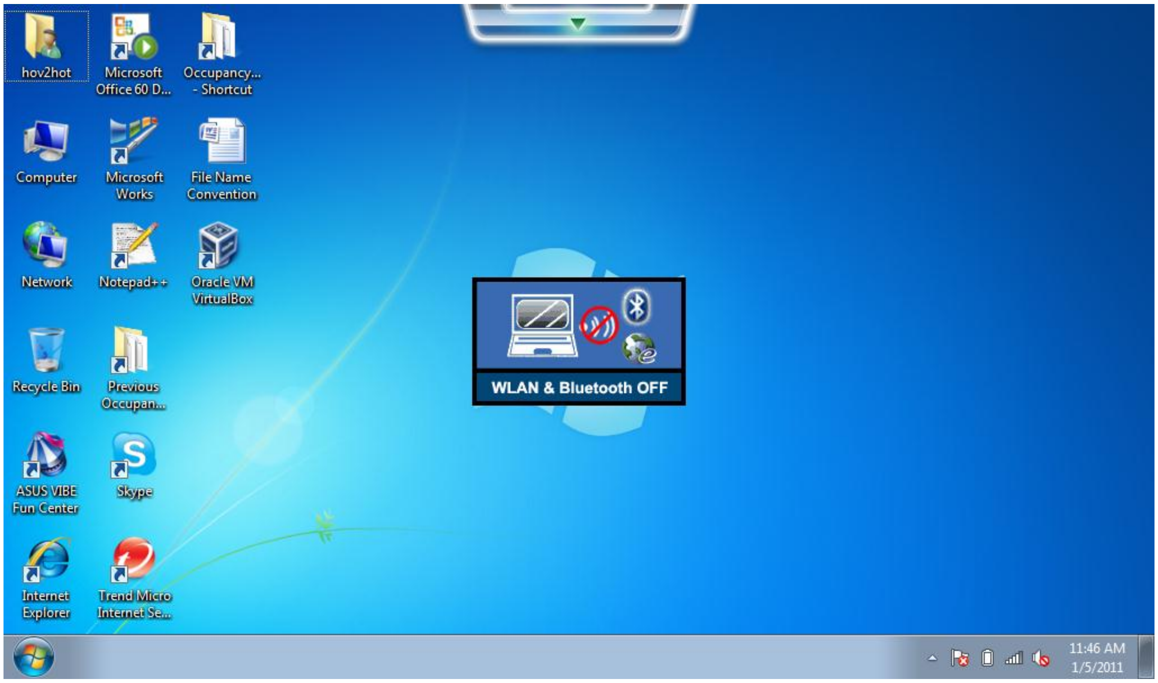


Figure 5. Disabling the netbook's wireless and Bluetooth adapters.

7. Select “Oracle VM VirtualBox” from the desktop.
8. After Oracle VM VirtualBox opens, select “Start” to launch the virtual machine.
    a. It will take several minutes for the virtual machine to boot up.
9. Ubuntu should automatically log you in and black menu bar should appear. If not, the password is “bluetooth123”.
    a. The right “Ctrl” key allows you to alternate between using the mouse within Ubuntu and within Windows. Alternatively, while the mouse is in Windows, you may click anywhere within the Ubuntu display to activate the pointer within Ubuntu. To alternate from using your mouse within Ubuntu to Windows, you must press the right “Ctrl” key.
10. In the virtual machine’s menu bar, select “Devices,” “USB Devices,” and “Broadcom Corp BCM” to attach the Bluetooth adapter to the virtual machine.
    a. If the attaching process is successful, a Bluetooth symbol will appear in the Ubuntu menu bar to the left of the battery icon. In addition, there will be a check mark to the left of “Broadcom Corp BCM” in the “USB Devices” menu. This is shown in figure 6.

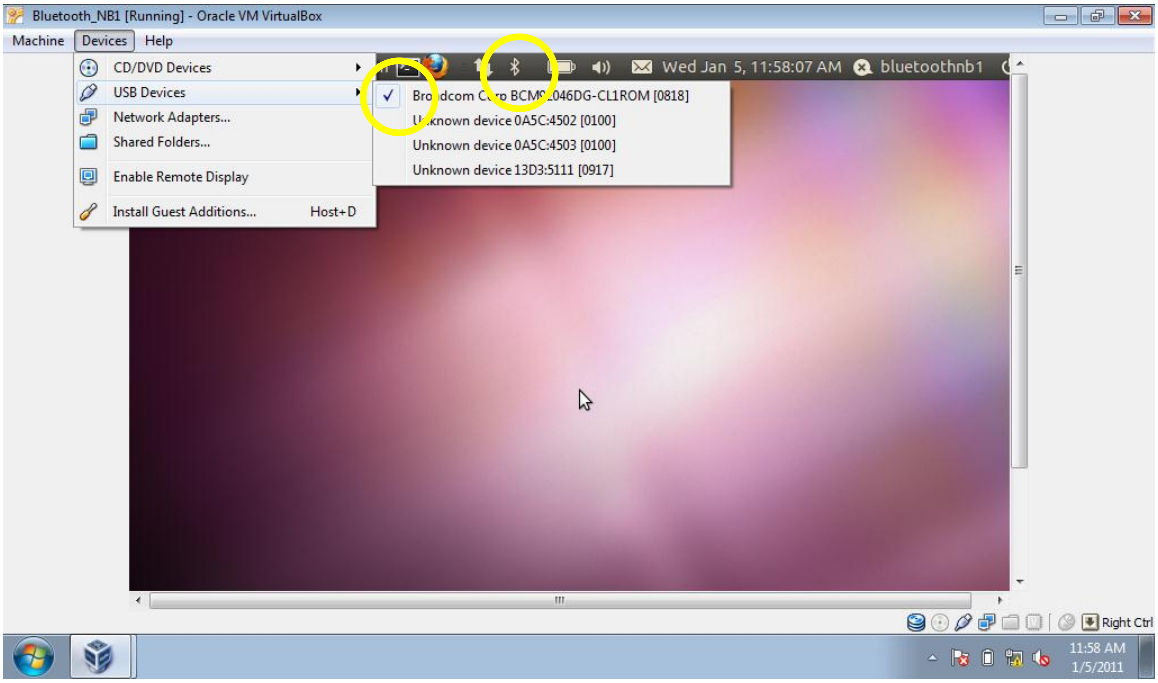


Figure 6. Successfully attaching Bluetooth adapter to Ubuntu.

b. If the attaching process is unsuccessful, remove and re-insert the Bluetooth adapter into the same USB port. Repeat the attaching process. Attempt this three times.

c. If the Bluetooth adapter will still not attach to the virtual machine, exchange the Bluetooth adapter with another adapter currently attached to another netbook.

11. In the Ubuntu menu bar, open the Terminal by selecting the symbol of the command prompt as shown in figure 7, located to the immediate left of the Mozilla Firefox icon. Repeat this step so that two Terminals are open.

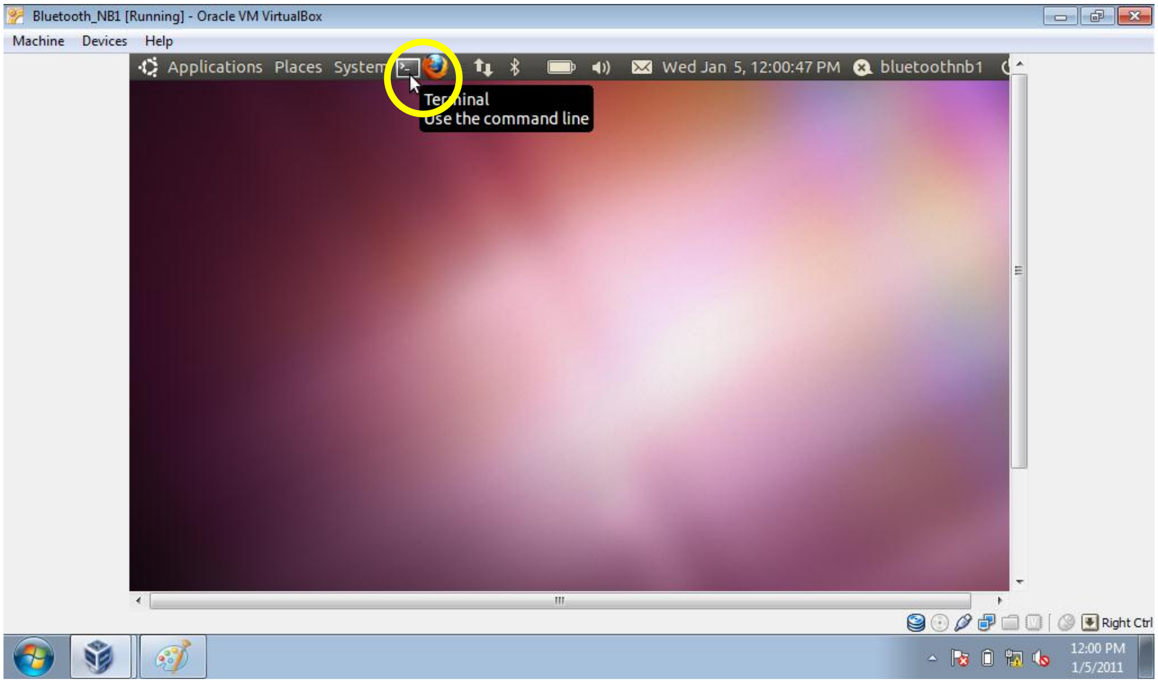


Figure 7. Opening the Terminal from the Ubuntu menu bar.

12. Resize the windows so that both fill up half of the Ubuntu screen as shown in figure 8. This may be done by moving the pointer over the edge of the Terminal window until an arrow is visible. Then click and drag to resize.

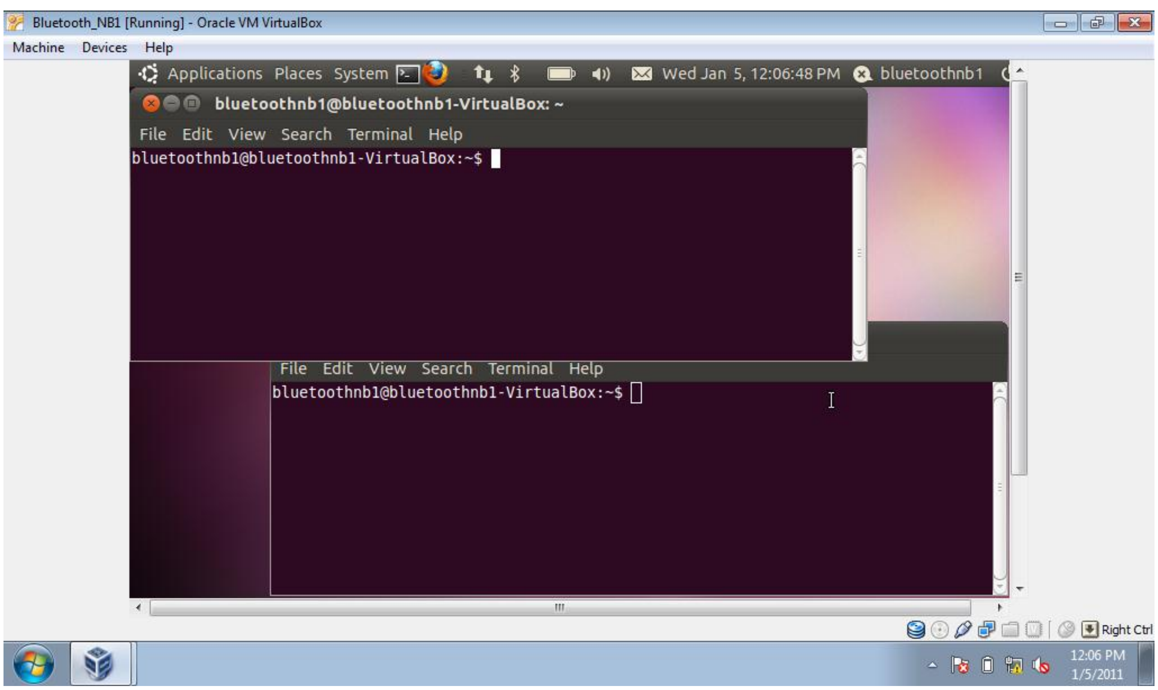


Figure 8. Resizing of Terminal windows for user observation.

13. [Optional] To view all of the scripts to verify your commands in steps 14 and 15, type "ls" in the Terminal and press enter.
    a. Note: "ls" is lowercase L and lowercase S.
14. In the first Terminal, type the command "PERL loop_hcitool.pl" and press enter.
    a. The Terminal window should now display the word "Scanning …"
    b. After a few moments, the MAC IDs and user-defined names of any discoverable Bluetooth devices within range of the Bluetooth adapter will appear.
15. In the second Terminal, type the command "PERL scan_id_#.pl", where "#" corresponds to the number on the Bluetooth adapter, and press enter.
    a. If an error occurs, this is because the initial script has not detected any Bluetooth devices yet. Allow the initial script a few more seconds, and reattempt step 15. If the command still experiences an error, a Bluetooth device may need to be activated in range of the Bluetooth adapter before using the second script.
    b. Every detection will now be displayed with the date, time, and MAC ID of each discoverable Bluetooth device.
    c. Each detection will be automatically logged into a .log file named "BT_LOG_test_#.log" where "#" corresponds to the number of the Bluetooth adapter.
16. Close the netbook to conserve battery power. The display will turn off, but the netbook will remain on.
17. After the data collection process is over, terminate each of the two scripts by pressing "Ctrl"+"z" while each terminal window is active, and close each terminal by selecting the "x" in the top-left corner of each window.
18. Shut down the virtual machine by selecting "x" in the top-right corner of the virtual machine window, select "Send the shutdown signal", press "OK", and select "Shut Down" in the Ubuntu screen.
    a. The right "Ctrl" key allows you to alternate between using the mouse within Ubuntu and within Windows. Alternatively, while the mouse is in Windows, you may click anywhere within the Ubuntu display to activate the pointer within

Ubuntu. To alternate from using your mouse within Ubuntu to Windows, you must press the right “Ctrl” key.

19. After Oracle VM VirtualBox has shut down, send the netbook to sleep mode by pressing the power button once.
20. Remove the Bluetooth adapter and close the netbook.

APPENDIX B
FIELD DEPLOYMENT PLAN

Overview

This field test is intended to determine the height at which Bluetooth readers should be placed to yield the greatest detection rate for the Buford Highway travel time study. A tripod equipped with four Bluetooth adapters at different heights will be placed at two different sites along Spring Street. The study segment, which is the length of roadway between the two sites, is approximately one mile long. This field test will take place on Friday, January 21, 2011. Setup will begin at 1:30pm, data collection will occur from 2:30pm to 6:30pm, and all test equipment will be removed by 7:30pm.

Using netbooks, Bluetooth adapters, Ubuntu, and PERL scripts, MAC addresses from Bluetooth devices in passing vehicles will be detected and recorded into log files for later travel time analysis. The devices detected will be compared across the four Bluetooth adapters at each tripod to determine the optimal placement height. Two Bluetooth adapters will be placed at the same height to provide validation of the data. Also, at each site a high definition video camera will be mounted in a vehicle parked nearby to gather data for traffic counts. This will allow the calculation of a match rate, which is the percentage of vehicles for which travel time was collected out of the total traffic volume. In addition, two probe vehicles will travel along Spring Street to provide ground-truth data for comparison of the travel times measured by the Bluetooth adapters. Each probe vehicle will be instrumented with three detectable Bluetooth devices and four GPS loggers.

Probe Vehicle Setup

Each probe vehicle will contain three netbooks, each equipped with one class 1 Bluetooth adapter on an USB extension cable. One adapter will be attached to the vehicle's dashboard, the second will be located on the front passenger seat of the vehicle, and the third will be positioned on the floor by the front passenger seat. The adapters will be in discovery mode so that they can be detected by the Bluetooth readers at the tripod locations. The unique MAC address and location in the vehicle of each Bluetooth adapter will be recorded prior to the start of the test. Each probe vehicle will also be outfitted with four GPS devices: a GlobalSat DG-100 Data Logger, a BT-335 GPS Logger. Each GPS device will be active during the study period. The GPS data will be transferred after returning to the lab.

The following list specifies the equipment for each probe vehicle:

Vehicle 1: Small Van

- ☐ Netbooks 9, 10, 11
- ☐ Sabrent Class 1 BT adapters 1, 2, 3

Vehicle 2:Pickup Truck

- ☐ Netbooks 12, 13, 0
- ☐ Sabrent Class 1 BT adapters 4, 5, 6

In addition, the following equipment is required in both vehicles:

- ☐ 1 GlobalSat DG-100 Data Logger
- ☐ 1 BT-335 GPS Logger

- ☐ 1 long USB extension cables
- ☐ 2 short USB extension cables
- ☐ Safety vest
- ☐ Tape to secure Bluetooth adapter to dashboard

Probe Vehicle Routes

The probe vehicles will depart from SEB no later than 1:45pm. Drivers will meet in the Trump Tower Surface Parking Lot and set up the equipment in the vehicles prior to beginning the experiment at 2:30pm.

Vehicle 1 will follow the red route shown in Figure 1, driving south on Spring Street in the right-most lane. The driver will then turn right on 4th Street, which becomes Williams Street, and make another right turn on to 16th Street. The vehicle will then turn right again on to Spring Street and repeat the loop for the duration of the test. One full loop on route 1 takes approximately 6-7 minutes, which will allow for roughly 35 passes by each tripod over the four hour test duration.

Vehicle 2 will follow the blue route shown in Figure 1, driving south on Spring Street in the left-most lane. The driver will then turn left on 3rd Street, left again on to West Peachtree Street, then left on to 16th Street. The vehicle will then turn left on to Spring Street and repeat the loop for the duration of the test. One full loop on route 2 takes approximately 10 minutes, which will allow for roughly 20 passes by each tripod over the four hour test duration.

The driving for each vehicle will be split into two shifts. The first shift will be from 2:30-4:30pm and the second shift will be from 4:30-6:30pm. Vehicle 1 will change drivers at the Georgia Tech Hotel driveway between 4th Street and 5th Street, across from Site 2. Vehicle 2 will change drivers in the Trump Tower surface parking lot where Site 1 is located.

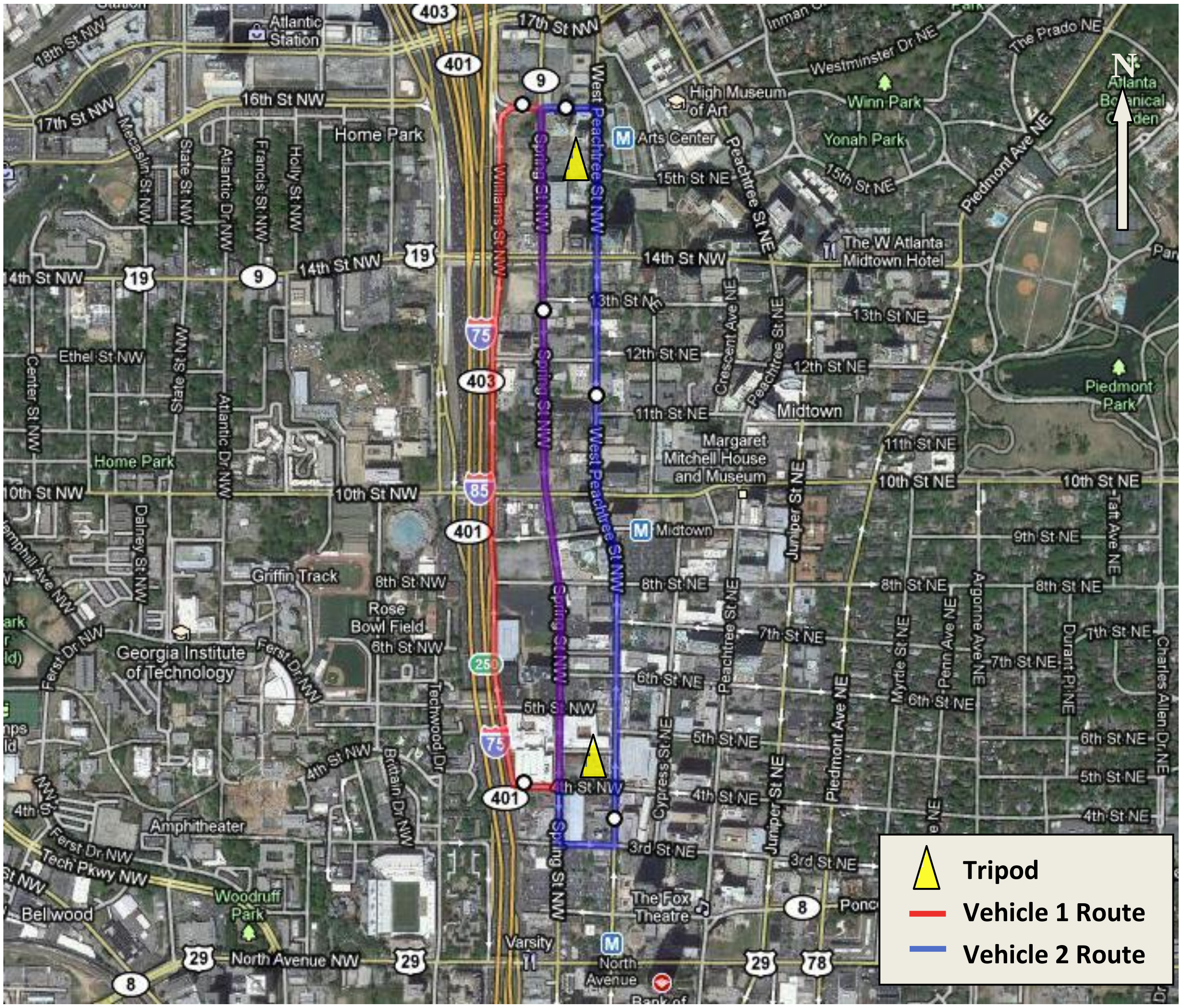


Figure 1: Probe vehicle driving routes.
Source: Google Maps, http://maps.google.com/, accessed January 21, 2011.

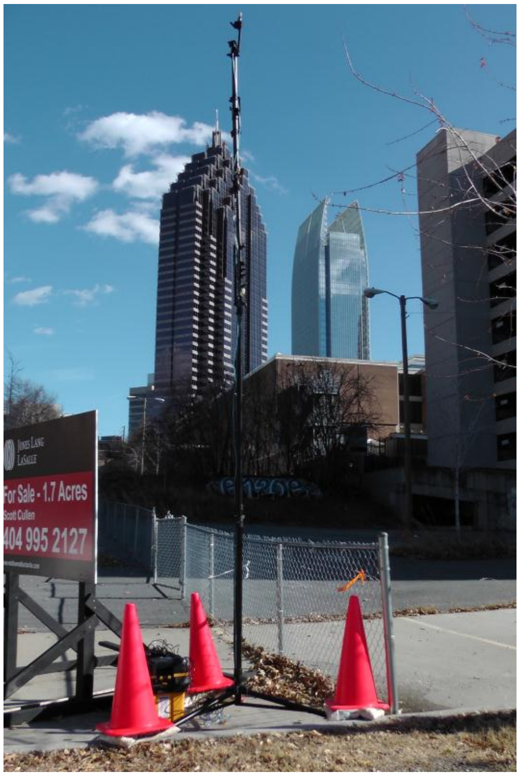
Tripod Locations

Site 1: Trump Tower Surface Parking Lot

The first site is a surface parking lot owned by Central Parking System at 1252 West Peachtree Street, Atlanta, GA 30309. Russell Miller, the general manager of Central Parking System lots in Atlanta, has given permission to use the site and may be reached at 404-525-9014 or rumiller@parking.com. The lot will be accessed via the Spring Street entrance. Graduate students will park in any available spot closest to the tripod setup location and pay at the pay station. An all-day parking pass will be purchased for $5.00 and placed on the dashboard of the parked vehicle.

Source: Google Maps, http://maps.google.com/, accessed January 21, 2011.

The tripod will be located in the southwest corner of the lot, with two of the tripod legs flush to the curb closest to Spring Street as shown in the photos below.



<u>Site 2: The Crum and Forster Building</u>

The second site is located in front of the Crum and Forster Building at 771 Spring Street, Atlanta, GA 30308. John B. Carter Jr., the President and Chief Operating Officer of the Georgia Tech Foundation, has given permission for a tripod to be set up on the brick area in front of the building. He may be reached at 404-894-0772 or john.carter@gtf.gatech.edu. Graduate students will park in the building's driveway.

Source: Google Maps, http://maps.google.com/, accessed January 21, 2011.

The tripod will be located on the south end of the brick area in front of the building. Two of the legs will be parallel to Spring Street, with one of the two flush against the southern wall of the brick area as shown in the pictures below.


Tripod Setup

Prior to departure, eight netbooks will be set up with Bluetooth adapters as described in Appendix A: Using the Netbooks, PERL Scripts, and Bluetooth Adapters to Collect MAC Addresses. The Bluetooth adapter number and netbook number should match and will correspond to the heights on the tripods listed below.

Number	Height
1, 2	7 ft
3, 4, 5, 6	10 ft
7, 8	14.5 ft

The date and time settings on the two cameras will be manually synchronized to match the netbook dates and times, which will already have been synchronized to an atomic time server as detailed in Appendix A. The odd-numbered netbooks will then be placed in the Site 1 bin using the filing trays. The Bluetooth adapters should be outside the bin, along with the premeasured length of cable that corresponds to the height of the adapter. The even-numbered netbooks will be organized in the same way in the Site 2 bin. All equipment will then be loaded into the appropriate vehicle for transfer to each site.

The following is a checklist of equipment that must be brought to each tripod location:

- ☐ 4 USB extension cables (10m)
- ☐ Wheeled field bin
- ☐ 6 Velcro ties
- ☐ 3 orange cones
- ☐ 2 safety vests
- ☐ 3 sandbags
- ☐ SD card for camcorder
- ☐ 2 batteries for camcorder
- ☐ Camcorder mount
- ☐ Measuring tape
- ☐ 3/16 Allen wrench
- ☐ Toolbox

Tripod 1:

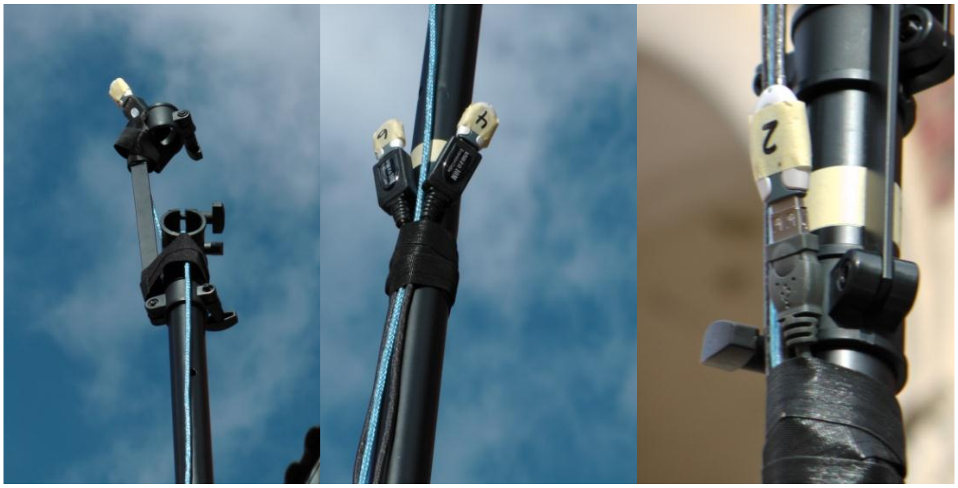
- ☐ Netbooks 1, 3, 5, and 7
- ☐ Bluetooth adapters 1, 3, 5, and 7
- ☐ Camcorder Alt 1

Tripod 2:

- ☐ Netbooks 2, 4, 6, and 8
- ☐ Bluetooth adapters 2, 4, 6, and 8
- ☐ Camcorder Alt 2

The drivers should leave from SEB no later than 1:30pm. Once the vehicles are parked at their respective sites, "Georgia Tech Students" signs will be placed in the front and rear windshields of the vehicles. Two persons will be needed to set up each tripod. Safety vests should be worn at all times while in the field.

The tripod should first be assembled along the ground with the legs folded. The Bluetooth adapters will then be attached to the tripod using the Velcro ties, starting with the adapter at 14.5 feet. The cable should be attached flush to the tripod and secured with a Velcro tie with the next two adapters at the 10 feet mark. Similarly, those three cables should be pulled taut and attached at the 7 feet mark with the final adapter. Two more Velcro ties will be used to secure the cables: one at approximately 4 feet and one at the base of the tripod. There will be 4 to 6 inches of extra cable beyond the Velcro tie for each adapter to ensure that the adapter is not touching the metal tripod. This will help in avoiding interference from the tripod.



Once the tripod is constructed and the Bluetooth adapters securely are attached, the legs will be unfolded to form the widest base possible. The tripod is then mounted vertically and positioned in its proper location as previously described. The setback from the road at both sites should be 22.5 feet. If the tripod is set-up flush to the curb at Site 1, no measuring will be required. The offset distance at Site 2 must be measured. While moving the tripod, care must be taken to ensure that the bin containing the netbooks is kept close enough to the tripod to avoid unplugging the cables from the netbooks. Once the tripod is erected, one person will hold the tripod steady while the other person positions one sandbag on each tripod leg and places a safety cone on each sandbag.

Finally, the camera will be mounted on the window of the parked vehicle so that all passing vehicles on Spring Street can be captured. Video will be recorded starting at 2:30pm, at which point the probe vehicles should begin to travel their respective routes.

REFERENCES

[1] S. M. Turner, *et al.*, "Travel Time Data Collection Handbook," Texas Transportation Institute, The Texas A&M University System, College Station, Texas1998.

[2] J. Chu. (2011, 29 March 2011). *Travel Time Messages on Dynamic Message Signs*. Available: http://ops.fhwa.dot.gov/travelinfo/dms/signs.htm

[3] E. Brandt. (2007, 29 March 2011). *How long will it take at rush hour?* Available: http://google-latlong.blogspot.com/2007/08/how-long-will-it-take-at-rush-hour.html

[4] R. Taylor, "Travel Time Reliability," F. H. Administration, Ed., 2006.

[5] R. Rupert. (2009, 29 March 2011). *Using Toll Tag Readers for Traffic Monitoring*. Available: http://ops.fhwa.dot.gov/publications/fhwahop08050/

[6] J. Wright and J. Dahlgren, "Using Vehicles Equipped with Toll Tags as Probes for Providing Travel Times," California Partners for Advanced Transit and Highways2000.

[7] N. Bradley. (2010) Collected development. *Traffic Technology International*. 48-53.

[8] J. Barceló, *et al.*, "Travel Time Forecasting and Dynamic OD Estimation in Freeways Based on Bluetooth Traffic Monitoring," Department of Statistics and Operations Research and CENIT2009.

[9] FDOT, "Chapter 14: Travel Time and Delay Study, Manual on Uniform Traffic Studies," 2000.

[10] A. Raqib, *et al.*, "Estimating Travel Time of Arterial Road Using Car Chasing Method and Moving Observer Method," *Journal of Transportation Science Society of Malaysia*, vol. 1, pp. 77-87, 2005.

[11] B. Hellinga and L. Fu, "Reducing Bias in Probe-Based Arterial Link Travel Time Estimates," *Transportation Research Part C*, pp. 257-273, 2007.

[12] M. P. Hunter, *et al.*, "Practical Procedure to Collect Arterial Travel Time Data Using GPS-Instrumented Test Vehicles," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1978, pp. 160-168, 2006.

[13] H. K. Kim, *et al.*, "A Case Study on Measuring Travel Time, Speed, and Delay Using GPS-Instrumented Test Vehicles," presented at the 9th International Conference on Applications of Advanced Technology in Transportation, Chicago, Illinois, 2006.

[14] J. Ko, *et al.*, "Measuring Control Delay Using Second-by-Second GPS Data," presented at the Transportation Research Board 2007 Annual Meeting, Washington, D.C., 2006.

[15] H. Li, *et al.*, "Using Global Positioning System Data to Understand Day-to-Day Dynamics of Morning Commute Behavior," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1895, pp. 78-84, 2004.

[16] S. Schonfelder, *et al.*, "Analysis of Commute Atlanta Instrumented Vehicle GPS Data: Destination Choice Behavior and Activity Spaces," presented at the Transportation Research Board 2006 Annual Meeting, 2006.

[17] M. Taylor, *et al.*, "Integration of the global positioning system and geographical information systems for traffic congestion studies," *Transportation Research Part C*, vol. 9, pp. 257-285, 2000.

[18] J. Jun, *et al.*, "Smoothing Methods to Minimize Impact of Global Positioning System Random Error on Travel Distance, Speed, and Accelerations," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1972, pp. 141-150, 2006.

[19] D. J. Dailey and F. W. Cathey, "AVL-Equipped Vehicles as Speed Probes (Final Phase)," 2005.

[20] W. Sarasua, *et al.*, "Use of GPS and GIS to Incorporate Grade and Vehicle Location into Transportation Air Quality Modeling," presented at the 6th CRC On-Road Vehicle Emissions Workshop, San Diego, California, 1996.

[21] M. Berkow, *et al.*, "Transit Performance Measurement and Arterial Travel Time Estimation Using Archived AVL Data," in *ITE District 6 Annual Meeting*, Portland, OR, 2007, pp. 1-10.

[22] R. L. Bertini and S. Tantiyanugulchai, "Transit Buses as Traffic Probes – Use of Geolocation Data for Empirical Evaluation," *Transportation Research Record: Journal of the Transportation Research Board*, pp. 35-45, 2003.

[23] J. Lin, "Probe based Arterial Travel time Estimation and Prediction – A case Study on using Chicago Transit Authority Bus Fleet as Probes," in *CTS-IGERT Seminar*, 2009.

[24] F. W. Cathey and D. J. Dailey, "Transit Vehicles as Traffic Probe Sensors," in *IEEE Intelligent Transportations Systems Conference*, Oakland, CA, 2001, pp. 579-584.

[25] D. A. Thornton, "Investigation of Using Radar Augmented Transit Buses as Arterial Travel Time Probes," Master of Science, Electrical & Computer Engineering, Ohio State University, 2009.

[26] J. Kennedy, *et al.*, "Highway Travel Time Analysis Using License Plate Image Capture Techniques," in *SPIE*, 2004, pp. 294-303.

[27] Y. Li, "Short-Term Prediction of Motorway Travel Time Using ANPR and Loop Data," *Journal of Forecasting*, vol. 27, pp. 507-517, 2008.

[28] C. Sun, *et al.*, "Vehicle Reidentification Using Multidetector Fusion," *IEEE Transactions on Intelligent Transportation Systems*, vol. 5, 2004.

[29] M. T. Volling, "Arterial Travel Time Using Magnetic Signature Re-Identification Theory of Application and Its Deployment in San Diego," presented at the ITS America, 2009.

[30] J. Wojtowicz, *et al.*, "RFID Technology for AVI: Field Demonstration of a Wireless Solar Powered E-ZPass Tag Reader," Center for Infrastructure and Transportation Studies, Rensselaer Polytechnic Institute, Troy, New York2008.

[31] K. Courage, *et al.*, "Improved Methods for Measuring Travel Time on Arterial Streets," Transportation Research Center, University of Florida, Gainesville, FL1998.

[32] (2011, 15 April 2011). *Bluetooth: About the Technology*. Available: http://www.bluetooth.com/Pages/About-the-Technology.aspx

[33] C. Franklin and J. Layton. (2000, 15 April 2011). *How Bluetooth Works*. Available: http://electronics.howstuffworks.com/bluetooth.htm

[34] J.-R. Jiang, *et al.*, "Analysis of Bluetooth Device Discovery and Some Speedup Mechanisms," *International Journal of Electrical Engineering*, 2004.

[35] R. Woodings, *et al.*, "Rapid Heterogeneous Connection Establishment: Accelerating Bluetooth Inquiry Using IrDA," in *The Third Annual IEEE Wireless Communications and Networking Conference*, Orlando, Florida, 2002.

[36] Logitech, Inc., "Bluetooth FAQ," 2005.

[37] A. Fredman, "Mechanisms of Interference Reduction for Bluetooth," Department of Electrical and Computer Engineering, University of Vermont, Burlington, VT2002.

[38] J. P. Lynch Jr., "Co-Channel Interference in Bluetooth Piconets," Master of Science, Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2002.

[39] IEEE Computer Society, "IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture." New York, NW, 2002.

[40] J. S. Wasson*, et al.*, "Real-Time Travel Time Estimates Using Media Access Control Address Matching," *ITE Journal,* pp. 20-23, 2008.

[41] D. dePencier, "Arterial/Freeway Performance Measurement Using MAC Reader Technology," in *ITE Gold Coast Chapter Meeting*, 2009.

[42] M. Martchouk and F. Mannering, "Analysis of Travel Time Reliability on Indiana Interstates," Purdue University2009.

[43] W. H. Schneider IV*, et al.*, "Statistical Validation of Speeds and Travel Times Provided by a Data Service Vendor," The University of Akron2010.

[44] K. Kim*, et al.*, "Evaluation of Technologies for Freeway Travel Time Estimation: A Case Study of I-287 in New Jersey," presented at the Transportation Research Board 2011 Annual Meeting, Washington, D.C., 2010.

[45] S. Young, "Bluetooth Traffic Monitoring Technology - Concept of Operation & Deployment Guidelines," University of Maryland - Center for Advanced Transportation Technology2008.

[46] "Bluetooth Travel Time Technology Evaluation - Using the BlueTOAD," KMJ Consulting, Inc., Haverford, PA2010.

[47] J. D. Porter*, et al.*, "Antenna Characterization for Bluetooth-based Travel Time Data Collection," presented at the Transportation Research Board 2011 Annual Meeting, Washington, D.C., 2010.

[48] Y. Malinovskiy*, et al.*, "Investigation of Bluetooth-Based Travel Time Estimation Error on a Short Corridor," presented at the Transportation Research Board 2011 Annual Meeting, Washington, D.C., 2010.

[49] T. M. Brennan Jr*, et al.*, "Influence of Vertical Sensor Placement on Data Collection Efficiency from Bluetooth MAC Address Collection Devices," *Journal of Transportation Engineering,* vol. 136, pp. 1104-1109, 2010.

[50] D. Nelson, "BluFax Applications," 2010.

[51] D. V. Boxel, *et al.*, "An Innovative Real-Time Methodology for Detecting Travel Time Outliers on Interstate Highways and Urban Arterials," presented at the Transportation Research Board 2011 Annual Meeting, Washington, D.C., 2010.

[52] D. D. Puckett and M. J. Vickich, "Bluetooth-Based Travel Time/Speed Measuring Systems Development," University Transportation Center for Mobility, Texas Transportation Institute2010.

[53] D. Nelson, "Use of Bluetooth-based Data Collection Opportunities and Challenges for Urban Corridor Studies," 2009.

[54] J. M. Roth, "A Time Series Approach to Removing Outlying Data Points from Bluetooth Vehicle Speed Data," Master of Science, The University of Akron, 2010.

[55] S. Quayle and P. Koonce, "Arterial Performance Measures using MAC Readers - Portland's Experience," in *North American Travel Monitoring Exposition & Conference*, 2010.

[56] A. Haghani and S. Young, "Bluetooth Traffic Monitoring - Technical Attributes and Applications," in *North American Travel Monitoring Exposition and Conference*, 2010.

[57] Y. Wang, *et al.*, "Field Experiments with Bluetooth Sensors," 2010.

[58] M. Asudegi, "Optimal Number and Location of Bluetooth Sensors for Travel Time Data Collection in Networks," Master of Science, Civil and Environment Engineering, University of Maryland, College Park, MD, 2009.

[59] A. Haghani, "Real Time Travel Time Evaluation," 2010.

[60] A. M. Hainen, *et al.*, "Estimating Route Choice and Travel Time Reliability using Field Observations of Bluetooth Probe Vehicles," presented at the Transportation Research Board 2011 Annual Meeting, Washington, D.C., 2010.

[61] K. Petty and J. Kwon, "Fusing Bluetooth Data and ITS Data for Performance Measurement," in *North American Travel Monitoring Exposition and Conference*, Seattle, WA, 2010.

[62] R. J. Haseman, *et al.*, "Real Time Measurement of Work Zone Travel Time Delay and Evaluation Metrics," *Transportation Research Board 2010 Annual Meeting*, pp. 1-23, 2010.

[63] E. O'Neill, *et al.*, "Instrumenting the City: Developing Methods for Observing and Understanding the Digital Cityscape," *Ubicomp,* vol. 4206, pp. 314-332, 2006.

[64] GDOT. (2010, 4 March 2011). *Georgia's State Traffic and Report Statistics (STARS)*. Available: http://www.dot.state.ga.us/statistics/stars/Pages/FultonTraffic.aspx

[65] (2011, 30 March 2011). *Google Maps*. Available: http://maps.google.com/

[66] (2009, 1 April 2011). *GlobalSat Bluetooth GPS + Data Logger: BT-335*. Available: http://www.usglobalsat.com/store/download/44/bt335_ds_ug.pdf

[67] (2004, 1 April 2011). *Qstarz Super 51-CH Performance Bluetooth GPS Travel Recorder: BT-Q1000*. Available: http://www.qstarz.com/Products/GPS%20Products/BT-Q1000.html

[68] F. A. Kaya and M. Santas, "A Computer Simulation of Dilution of Precision in the Global Positioning System Using MATLAB," Gazi University, Maltepe, Ankara, Turkey2005.

[69] C. Hodgon, "Adaptive Frequency Hopping for Reduced Interference between Bluetooth and Wireless LAN," *D&R Industry Articles,* 2003.